The impact of penalty and subsidy mechanisms on the decisions of the government, businesses, and consumers during COVID-19 ——Tripartite evolutionary game theory analysis

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ABSTRACT

Purpose: – Based on the fact that punishment and subsidy mechanisms affect the anti-epidemic incentives of major participants in a society, the issue of this paper is how the penalty and subsidy mechanisms affect the decisions of governments, businesses, and consumers during Corona Virus Disease 2019 (COVID-19).
Design/Methodology/approach: - This paper proposes a tripartite evolutionary game theory, involving governments, businesses, and consumers, to analyze the evolutionary stable strategies and the impact of penalty and subsidy mechanism on their strategy selection during COVID-19. We then uses numerical analysis to simulate the strategy formation process of governments, businesses, and consumers for the results of tripartite evolutionary game theory.
Findings: – This paper suggests that there are four evolutionary stable strategies corresponding to the actual anti-epidemic situations. We find that different subsidy and penalty mechanisms lead to different evolutionary stable strategies. High penalties for businesses and consumers can prompt them to choose active prevention strategies no matter what the subsidy mechanism is. For the government, the penalty mechanism is better than the subsidy mechanism, because the excessive subsidy mechanism will raise the government expenditure. The punishment mechanism is more effective than the subsidy mechanism in realizing the tripartite joint prevention of the COVID-19. Therefore, the implementation of strict punishment mechanism should be a major government measure under COVID-19.
Originality/value: - Our paper extends the existing theoretical work. We use political economy to make the preference hypothesis, and we explicitly state the effect of subsidy and penalty mechanisms on the decision making of participants and compare their applicability. This is the work that the existing literature did not complete before. Our findings can provide an important theoretical and decision-making basis for COVID-19 prevention and control.

1. Introduction

1.1. Background

The ongoing COVID-19 epidemic has presented an unprecedented threat to the every country on earth. Not all countries have responded equally, however. Among other factors, the extent to which government successfully implements public health policies aimed at controlling the pandemic determines the level of harm suffered. To successfully fight the pandemic, governments, businesses, and consumers must work together. As prior work in game theory has shown [2], cooperation cannot be guaranteed even with shared goals. To understand why some countries have seen greater success than others in controlling the pandemic we must consider the strategic situation in which government, businesses, and individuals interact with one another. Without broad cooperation, the impacts of COVID-19 are unlikely to be successfully mitigated even if the medical infrastructure of a country seems up to the task.

In some countries, governments, businesses, and consumers are working together to take proactive preventive action against COVID-19. Why have not all countries been able to do this? Although there are doubtless many contextual factors which influence this, in this paper we

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consider the broad incentives for cooperation using the tools of game theory.

We begin with the assumption that participants (including government, businesses, and individuals) will choose to actively fight the pandemic. This choice can maximize their utility. If an actor sees the all-things-considered payoff from non-cooperation as higher than that of cooperation they will choose not to cooperate. We assume that general cooperation is the socially optimal outcome here, but this outcome cannot be guaranteed as it is only one of several possible equilibria resulting from the individual players pursuing their own objectives. This leads us to our first research question:

RQ1: Whether there is a strategy profile, which enables governments, businesses, and consumers to meet their respective utility maximization during COVID-19?

In investigating question 1, it will become apparent that broad cooperation among government, business, and citizens to actively counter the pandemic is only one of several possible social outcomes. Assuming this is the socially optimal choice, the relevant question to ask is whether and how such an outcome can be achieved in an incentive-compatible manner. We divide the incentive structure into "internal" and "external" components. The internal incentive structure includes factors such as citizens' trust in government, preferences over health and personal autonomy, etc. Although these are not immutable, they are relatively stable in the short term and unlikely to be influenced by public policy interventions or institutional changes. The external incentive structure includes material incentives, including the inducements and penalties implemented by government. The external incentive structure is therefore more variable and may change quite rapidly during a pandemic in a way which could shift individual choices and social outcomes.

To consider how such changes in the external incentive structure can influence choices and outcomes we model the impact of penalty and subsidy mechanisms on strategy choice and equilibrium using tripartite game theory, first in general terms and then numerically using plausible assumptions about the relative values of key parameters. Thus, our second research question:

RQ2: How the penalty and subsidy mechanisms impact the resulting equilibria?

We will do a detailed literature review in the section 2. We contribute to the existing literature by expanding the work of Zhi et al. [16]. Zhi et al. [16] described how the mechanism of penalties and subsidies works for governments, businesses and citizens in public health situations. They concluded that proper subsidies, punishment mechanisms and public incentives would lead to tripartite cooperation to fight the pandemic. However, their study had two limitations: 1. They did not make assumptions about different preferences of citizens based on the political economics. 2. They did not compare the applicability of subsidy versus penalty mechanisms. The findings of their study, "*Numerical analysis results show that formulating reasonable subsidy measures, encouraging the participation of the public, and enforcing the punishment to enterprises for their negative behaviors can prompt three parties to cooperate in fighting against the epidemic*" (pp. 1), does not make clear how the mechanism of penalties and subsidies affects the decisions of governments, businesses and citizens. Therefore, on the basis of their work, we make two contributions: 1. We use political economy to assume that citizens have different preferences. 2. We clearly describe how the mechanism of punishment and subsidy affects governments, businesses and citizens decision making. We also compare the applicability of penalty and subsidy mechanisms. Our paper will provide an important theoretical basis for the development of national pandemic control policies.

The rest of this paper is structured as follows: The main contents in section 2 is literature review. We outline the assumptions and construction of the model in Section 3. In section 4, we provide solutions and analysis for both the general case based on plausible assumptions about key parameters. Conclusion and discussion is in section 5.

2. Literature review

There has been much economic research conducted on the topic of decision-making during the COVID-19 pandemic. This divides broadly into two forms: empirical analysis of the impact of pandemic control policies on behavior, and the use of game theory to theoretically model the choices of governments, businesses, and citizens.

Chen, et al. [1] empirically studied the driving factors of citizens' satisfaction with government responses. They found that citizens are more concerned with the outcomes of COVID-19 control than the specific policies implemented by the government. They also found that citizens' satisfaction with the government's response varies greatly from country to country. They suggest that when implementing pandemic control policies governments try to strike a balance between public health concerns (saving lives) and economic impacts (saving jobs), with different governments making different trade-offs between these competing objectives.

In studying the impact of policy decisions on mortality, Silva and Tsigaris [8] found that policy delays (in e.g. travel restrictions and public advocacy campaigns) increased mortality. Chen et al. [1] studied the impact of restrictive policies on COVID-19 in East Asia. They found that the incidence of COVID-19 decreased after the implementation of a restrictive policy intervention. They argue that citizens' responsibility, collectivism, and vigilance assisted East Asian countries in successfully controlling COVID-19.

Other studies have investigated the informational impact of the government response on pandemic control. In a pre-COVID-19 context, Kim and Liu [4] had studied how governments should respond to a pandemic. They considered that the best response would be transparency and accountability. Vallejo and Ong [9] researched the Philippine government's response to the COVID-19 outbreak, demonstrating that transparency and good information delivery mechanisms are key to dealing with public events.

The above quantitative studies provide important evidence about the effectiveness of pandemic policies but provide only limited insight about the strategic considerations which drive the choices of governments, businesses, and individuals. This is where game theory can add value, and a number of studies have analyzed various aspects of the pandemic using this approach.

Kumar et al. [5] studied the influence of social distance on the development of COVID-19 using non-cooperative game theory. They used non-cooperative games to provide citizens with incentives to keep social distance in order to prevent the spread of COVID-19, finding a Nash equilibrium to show the sustainability of restrictive policies. This study provides important insights into the incentives of players in a static game but did not consider the long-term dynamics or the possibility of behavior which is irrational or based on poor information. The latter point is particularly important in the context of COVID-19 since misinformation and conspiracy theories are rife in this context. Prominent claims spread on social media include the ideas that the virus is caused by 5G towers or that the vaccines contain microchips. There is also widespread misinformation on infection and fatality rates. Exposure to such misinformation has been shown to change beliefs and reduce preventive behaviors.

Murat and Burhaneddin [6] studied the phased effects of isolation using non-cooperative games. They divided the development of COVID-19 into three phases: the start, the spread, and the end. They used South Korea, Italy, and Turkey as examples to study the impact of quarantine on the development of the pandemic. The results show that isolation has an important impact on the scale of infection and the development of the pandemic. This study introduces some dynamic

elements by using repeated games to verify the necessity of continuous isolation. There are two limitations here, however. First, as above, the authors use a straightforward rationality assumption and do not account for imperfect information. Secondly, it does not consider the strategic situation facing governments and the incentives they have to implement policies to combat the pandemic. This is an important determinant of effective pandemic control, and countries vary in this respect.

Social distancing requirements force businesses to limit the number of customers at any given time. Yael and Uri [13] use game theory to study the relationship between queuing time and infection risk and the incentives facing businesses and consumers. They find that risk of infection is proportional to the number of customers. Although this paper provides useful knowledge on this particular part of pandemic control, the scope is much narrower than the present study.

Wei, et al. [10] established the transmission frequency equation of COVID-19. By combining an evolutionary game analysis of the actions from the government and the public in the early stages of the epidemic into a model of the natural transmission mechanism, they found the government's emergency response strategy in the early days of the outbreak has been effective in controlling the spread of the virus. Ngonghala, et al. [7] combined the transmission dynamics of COVID-19 with the multi-strategy evolutionary game method of individual decision making. They found that social distancing played an important role in reducing the burden of disease compared to self-isolation. In order to significantly reduce disease transmission, there should be a high proportion of individuals to achieve social distancing. Yong and Bryan [15] use evolutionary game theory and public goods to provide an important framework for understanding cooperation during epidemics. They found that in addition to NPIs, targeted programs to promote vaccination can reduce free-riding and improve compliance with social conditions. They argue that penalties and subsidies, as well as other various economic incentives, must be matched to increase the benefits of compliance. Xu, et al. [12] constructed a tripartite evolutionary game model of local government, enterprises and the public in COVID-19 and other public health emergencies. They discussed the evolutionary stability strategy under different conditions of tripartite evolutionary game and analyzes the influence of different factors on the decision-making of participants in public health emergencies. The results of numerical analysis show that appropriate subsidy measures, encouragement of public participation and punishment of enterprises' negative behaviors can promote tripartite cooperation to fight the epidemic.

Yan et al. [14] aimed to explore the process of tourism recovery in the post-COVID-19 era. By constructing an evolutionary game model between the government, tourists, and tourism enterprises, he found that the development and change of public health emergencies affect the behavioral strategies of tourism stakeholders. In addition, strategic options for each participant, including governments, tourism businesses and tourists, are also evolving through the different phases of the pandemic. Xiao, et al. [11] studied the spillover effects of cross-regional nature and public health outbreak management. Using the regional evolutionary game analysis framework, they found that when the regional spillovers and governance costs are small, or the economic and social damage caused by public health emergencies is large, all regions will choose to cooper ate. Otherwise, there will be regions that chose to "free ride". The "free ride" leads to the failure of good cross-regional collaborative governance in public health emergencies, and it also leads to the low efficiency of the overall governance of social public health.

3. Model Assumptions

Basic Assumption: We define a tripartite game space $\Omega = \{N, \Lambda, \{S_i\}, \{U_i(\cdot)\}\}_{i \in N}$, where $N = \{1, 2, 3\}$ (1 represents the government, 2 represents businesses and 3 represents consumers) is the participant set and $\{A_i\}_{i \in N} \subset \Lambda$ represents the player's ith action set ($A_G =$ {Implement, Non − implement}, $A_M = A_C =$ {Active prevention, Negative prevention}). $S_i = \{s_i^{(1)}, s_i^{(2)}, \ldots, s_i^{(n)}\}_{i \in N}$ denotes the participant ith strategy set, that is participant i has n strategies. Their hybrid strategy σ_i is a probability distribution over $S_i = \{s_i^{(1)}, s_i^{(2)}, \ldots, s_i^{(n)}\}_{i \in N}$, namely, $\sigma_i : S_i \to [0, 1]$. $\{U_i(\cdot)\}_{i \in N}$ represents the payoff of the participant i (the choice of actions by all players determines an outcome $z \in Z$ of the game). Thus, $U_i : Z \to \mathbb{R}$.

In the context of COVID-19, we choose the government, businesses, and consumers as game players. The actions of the government are to implement strict restrictive policies and not to implement strict restrictive policies. There are the two options for both businesses and consumers to choose: active prevention and negative prevention. Table 1 shows the static payoff matrix of a tripartite game.

Assumption 1. The government has three broad objectives: Increasing the social welfare of citizens; Increasing re-election prospects by improving public opinion and Increasing government revenue net of spending in order to fund activities to pursue the above two objectives.

We assume, therefore, that the utility of the government consists of three parts: welfare utility, re-election utility, and financial utility. Anti-pandemic policies such as mask mandates, lockdowns, and vaccine subsidies have both benefits and costs in terms of these three objectives. Actively fighting the pandemic will increase social welfare by improving health outcomes but many policies (e.g. lockdowns, social distancing requirements) could also reduce economic activity and thus reduce social welfare. Given the extreme nature of the situation and the success countries have had when tackling the pandemic early, we assume that social welfare will be maximized with a strong policy response.

Depending on the preferences of citizens, active public health policy could either increase or decrease re-election prospects. Those citizens concerned with their health and worried about the pandemic will reward government by voting for them at the next election if the virus is successfully controlled (i.e. retrospective voting based on pandemic outcomes) and for enacting policies which are seen as proactive. Citizens who value freedom over health or are skeptical of the threat of the pandemic, on the other hand, will vote against incumbent government who impose strict policies. The relative proportion of these different types of voters in a population is therefore important. Finally, different policy choices will have different fiscal implications for government. Fines for noncompliance could bring in money, while subsidies, enforcement of policies, and research funding will all be costly.

We thus assume that government gains basic social welfare utility $u_b \in \mathbb{R}_+$ if it imposes strict pandemic policy. To consider re-election utility, we distinguish two citizen types: "health-centred" (i.e. those who value pandemic control above other factors in the context of the COVID-19 pandemic and support strict policy imposed by government) and "freedom-centred" citizens (i.e. those who value other factors such as consumption and freedom above pandemic control and thus oppose strict policies). On this basis, if the businesses and the consumers are health-centred and choose to cooperate with pandemic control, the additional positive utility $\{R_M^j\}_{j=1}^{\infty} \subseteq \mathbb{R}_+$ and $\{R_C^{aj}\}_{j=1}^{\infty} \subseteq \mathbb{R}_+$ will be given to the government. If the businesses and consumers are freedom-centred and choose not to cooperate, the additional utility to the government are $\{R_C^{rj}\}_{j=1}^{\infty} \subseteq \mathbb{R}_-$ and $\{R_C^{rj}\}_{j=1}^{\infty} \subseteq \mathbb{R}_-$, respectively.

When the government chooses not to impose strict restrictions, it gains a basic utility of 0 and if consumers and businesses choose active prevention, they give the government a negative additional utility $-\{R_C^{aj}\}_{j=1}^{\infty} \subseteq \mathbb{R}_-$. Of course, the government also will receive fines $\{c_p^i\}_{i \in N \setminus \{1\}} \subseteq \mathbb{R}_+$ from businesses and consumers if they do not cooperate when the government imposes restrictions. Similarly, we assume that if the government chooses to impose strict restrictions, it will pay a basic cost $c_0 \in \mathbb{R}_+$. If the businesses and the consumer choose active prevention, the additional cost to the government is 0; If businesses and consumers choose negative prevention, the additional cost to the

Table 1

Payoff matrix for the government, businesses, and consumers.

| Government | Businesses × Consumers | | | |
	Active prevention, Negative prevention	Active prevention, Active prevention	Negative prevention, Negative prevention	Negative prevention, Active prevention
Implement	a_{11}, a_{12}, a_{13}	a_{14}, a_{15}, a_{16}	a_{17}, a_{18}, a_{19}	$a_{110}, a_{111}, a_{112}$
Non-implement	a_{21}, a_{22}, a_{23}	a_{24}, a_{25}, a_{26}	a_{27}, a_{28}, a_{29}	$a_{210}, a_{211}, a_{212}$

Note: Due to the limited space, it is difficult for us to directly represent each game result in Table 1 using utility $U_i(\cdot)$. So, for the ease of expression and reading, we let $a_{11} = U_1(s_1^I, s_2^{AP}, s_3^{NP}), a_{12} = U_2(s_2^{AP}, s_1^I, s_3^{NP}), a_{13} = U_3(s_3^{NP}, s_1^I, s_2^{AP}), a_{14} = U_1(s_1^I, s_2^{AP}, s_3^{AP}), a_{15} = U_2(s_2^{AP}, s_1^I, s_3^{AP}), a_{16} = U_3(s_3^{AP}, s_1^I, s_2^{AP}), a_{17} = U_1(s_1^I, s_2^{NP}, s_3^{NP}), a_{18} = U_2(s_2^{NP}, s_1^I, s_3^{NP}), a_{19} = U_3(s_3^{NP}, s_1^I, s_2^{NP}), a_{110} = U_1(s_1^I, s_2^{NP}, s_3^{AP}), a_{111} = U_2(s_2^{NP}, s_1^I, s_3^{AP}), a_{112} = U_3(s_3^{AP}, s_1^I, s_2^{NP}), a_{21} = U_1(s_1^{NI}, s_2^{AP}, s_3^{NP}), a_{22} = U_2(s_2^{AP}, s_1^{NI}, s_3^{NP}), a_{23} = U_3(s_3^{NP}, s_1^{NI}, s_2^{AP}), a_{24} = U_1(s_1^{NI}, s_2^{AP}, s_3^{AP}), a_{25} = U_2(s_2^{AP}, s_1^{NI}, s_3^{AP}), a_{26} = U_3(s_3^{AP}, s_1^{NI}, s_2^{AP}), a_{27} = U_1(s_1^{NI}, s_2^{NP}, s_3^{NP}), a_{28} = U_2(s_2^{NP}, s_1^{NI}, s_3^{NP}), a_{29} = U_3(s_3^{NP}, s_1^{NI}, s_2^{NP}), a_{210} = U_1(s_1^{NI}, s_2^{NP}, s_3^{AP}), a_{211} = U_2(s_2^{NP}, s_1^{NI}, s_3^{AP}), a_{212} = U_3(s_3^{AP}, s_1^{NI}, s_2^{NP})$. Where s_i^j denotes the strategy of player i based on action j, and $AP = $ active prevention, $NP = $ negative prevention, $NI = Non - implement, I = implement$. For example, s_3^{AP} represents the strategy when consumers taking active prevention action. Thus, $U_3(s_3^{AP}, s_1^{NI}, s_2^{NP})$ means consumers' net payoff when consumers taking active prevention action, the government taking non-implement action and business taking negative prevention action.

government is $\{c_i^G\}_{i \in N \setminus \{1\}} \in \mathbb{R}_+$. If the government imposes strict restrictions, the government will subsidize (it is the cost for the government) the businesses or consumer, namely, the cost of the subsidy $\{S_G^i\}_{i \in N \setminus \{1\}} \subseteq \mathbb{R}_+$.

According to net payoff equals to total payoff minus cost, therefore, we can have the government whole net payoff as follows: $a_{14} = U_1(s_1^I, s_2^{AP}, s_3^{AP}) = u_b + R_M + R_C^a - c_0 - S_G^M - S_G^C, a_{110} = U_1(s_1^I, s_2^{NP}, s_3^{AP}) = u_b + R_C^a + c_p^M - S_G^C - c_0 - c_M^G, a_{27} = U_1(s_1^{NI}, s_2^{NP}, s_3^{NP}) = u_b, a_{21} = U_1(s_1^{NI}, s_2^{AP}, s_3^{NP}) = -R_M, a_{24} = U_1(s_1^{NI}, s_2^{AP}, s_3^{AP}) = -R_M - R_C^a, a_{210} = U_1(s_1^{NI}, s_2^{NP}, s_3^{AP}) = -R_C^a, a_{11} = U_1(s_1^I, s_2^{AP}, s_3^{NP}) = u_b + R_M + c_p^C - S_G^M - c_0 - c_c^G - R_C^r, a_{17} = U_1(s_1^I, s_2^{NP}, s_3^{NP}) = c_p^C + c_p^M + u_b - c_0 - R_M - R_C^r$. Whether the government should implement restrictions depends on which option maximizes its net utility. In order to encourage the government to better fight the epidemic, we assume that $a_{14} = U_1(s_1^I, s_2^{AP}, s_3^{AP}) > a_{24} = U_1(s_1^{NI}, s_2^{AP}, s_3^{AP})$ and $a_{27} = U_1(s_1^{NI}, s_2^{NP}, s_3^{NP}) > a_{17} = U_1(s_1^I, s_2^{NP}, s_3^{NP})$

We assume that $x \in [0, 1]$ probability of the government chooses to implement strict restrictive policies and $1 - x$ probability of the government participants chooses to not implement strict restrictive policies.

Assumption 2. The total utility of consumers is mainly composed of five parts: The health utility of consumers; Other utilities for consumers including consumption, entertainment, freedom, etc; The wages of consumers (monetary utility); Subsidies from the government as mentioned above in the government assumptions; Subsidies from businesses. In some countries, companies offer freely health subsidies to consumers, including free masks and disinfectant.

We assume that for all consumers, their utility consists of two parts: health utility $u_h \in \mathbb{R}_+$ and other utility $u_o \in \mathbb{R}_+$. For health-centred consumers, their health benefits outweigh other benefits. For freedom-centred consumers, their other utility is greater than the health utility. Therefore, regardless of the strict restrictive measures adopted by the government, freedom-centred consumers gain other utility $u_o \in \mathbb{R}_+$, and health-centred consumers gain health utility $u_h \in \mathbb{R}_+$. Consumers will pay three kinds of costs: medical costs $c_m^C \in \mathbb{R}_+$, other consumption costs $c_o^C \in \mathbb{R}_+$ and punishment cost $c_p^C \in \{c_p^i\}_{i \in N \setminus \{1\}} \subseteq \mathbb{R}_+$. The income structure of consumers is a basic wage $W_0 \in \mathbb{R}_+$ plus performance wage $W \in \mathbb{R}_+$. If the businesses choose active prevention the epidemic, the consumers receive only a basic wage, because companies will require employees to keep social distancing and even work at home. Thus, employee performance will be significantly lower than usual. If the businesses choose negative prevention, while the consumers choose active prevention, then the consumers' total wage is 0, because employees will opt for keeping social distance in order not to get infected, which makes them unwilling to go to work. As companies opt for negative prevention, employees who keeping in social distance are

considered absenteeism. If both the businesses and consumers choose negative prevention, the consumers can get all the wages. If businesses choose active prevention, or the government choose to implement the restrictions, consumers will receive subsidies $S^M \in \mathbb{R}_+$ or $S_G^C \in \{S_G^i\}_{i \in N \setminus \{1\}} \subseteq \mathbb{R}_+$.

According to net payoff equals to total payoff minus cost, therefore, we can have consumers net payoff as follows: $a_{26} = U_3(s_3^{AP}, s_1^{NI}, s_2^{AP}) = u_h + W_0 + S^M - c_o^C, a_{212} = U_3(s_3^{AP}, s_1^{NI}, s_2^{NP}) = u_h - c_o^C, a_{16} = U_3(s_3^{AP}, s_1^I, s_2^{AP}) = u_h + W_0 + S^M + S_G^C - c_o^C, a_{112} = U_3(s_3^{AP}, s_1^I, s_2^{NP}) = u_h + S_G^C - c_o^C, a_{23} = U_3(s_3^{NP}, s_1^{NI}, s_2^{AP}) = u_o + W_0 + W - c_m^C - c_o^C + S^M, a_{29} = U_3(s_3^{NP}, s_1^{NI}, s_2^{NP}) = u_o + W_0 + W - c_m^C - c_o^C, a_{19} = U_3(s_3^{NP}, s_1^I, s_2^{NP}) = u_o + W_0 + W - c_m^C - c_o^C - c_p^C, a_{13} = U_3(s_3^{NP}, s_1^I, s_2^{AP}) = u_o + W_0 + W - c_m^C - c_o^C - c_p^C + S^M$. Whether consumers should take active prevention depends on which option maximizes their net utility. The utility of consumers are higher in choosing to fight the epidemic when both other players choose to fight the epidemic, we assume that $a_{29} = U_3(s_3^{NP}, s_1^{NI}, s_2^{NP}) > a_{212} = U_3(s_3^{AP}, s_1^{NI}, s_2^{NP})$ and $a_{16} = U_3(s_3^{AP}, s_1^I, s_2^{AP}) > a_{13} = U_3(s_3^{NP}, s_1^I, s_2^{AP})$.

We assume that $y \in [0, 1]$ probability of consumers choosing active prevention with the government and $1 - y$ probability of the consumers choosing negative prevention.

Assumption 3. The utility of businesses mainly consists of two parts: First, the profit of businesses. It also can be divided into two parts: basic profit and performance profit. Basic profit refers to the profit that an enterprise can get regardless of whether a pandemic occurs. Profit for performance refers to the extra profit an enterprise can get (During COVID-19, employees working at home have reduced the enterprise output. We take the sales staff as an example. Due to the government's restrictive policies, the sales staff cannot sell products outside, which results the profits decreasing. This is performance profits). Second, the government subsidies during COVID-19 as we have mentioned before. The main costs to the businesses are as follows: consumer wages, enterprise-to-consumer subsidies, and penalties paid by the businesses for breaking restrictive policies.

If the government chooses implement restrictions, on the one hand, businesses will not receive the government subsidies. On the other hand, they will not have to pay penalty costs. If consumers are freedom-centred, businesses will not pay the enterprise-to-consumer subsidies. This is because the companies gives employees health subsidies to guarantee health-centred consumers' right, such as sending masks, disinfectant for free.

Therefore, the net utility of businesses is the difference between their total utility and total costs. Whether businesses should take active prevention depends on which option maximizes their net utility.

Thus, the profit of businesses consists of two parts: basic profit $\pi_0 \in \mathbb{R}$ and performance profit $\pi \in \mathbb{R}$. If the government imposes strict re-

strictions and businesses choose to take active prevention, they will receive subsidies $S_G^M \in \{S_G^i\}_{i \in N \setminus \{1\}} \subseteq \mathbb{R}_+$ from the government. The cost of the businesses mainly consists of the base wage $W_0 \in \mathbb{R}_+$ and performance wage $W \in \mathbb{R}_+$ of the consumers. If the government imposes strict restrictions while the businesses does not cooperate (taking negative prevention), the businesses will pay penalty costs $c_p^M \in \{c_p^i\}_{i \in N \setminus \{1\}} \subseteq \mathbb{R}_+$.

Therefore, the net utility of businesses is the difference between their total utility and total costs. Thus, we can have businesses whole net payoff as follows: $a_{28} = U_2(s_2^{NP}, s_1^{NI}, s_3^{NP}) = \pi_0 + \pi - W_0 - W$, $a_{211} = U_2(s_2^{NP}, s_1^{NI}, s_3^{AP}) = \pi_0 - W_0$, $a_{18} = U_2(s_2^{NP}, s_1^I, s_3^{NP}) = \pi_0 + \pi + S_G^M - W_0 - W - c_p^M$, $a_{111} = U_2(s_2^{NP}, s_1^I, s_3^{AP}) = \pi_0 + S_G^M - W_0 - c_p^M$, $a_{15} = U_2(s_2^{AP}, s_1^I, s_3^{AP}) = \pi_0 + S_G^M - W_0 - S^M$, $a_{12} = U_2(s_2^{AP}, s_1^I, s_3^{AP}) = \pi_0 + \pi + S_G^M - W_0 - W - S^M$, $a_{25} = U_2(s_2^{AP}, s_1^{NI}, s_3^{AP}) = \pi_0 - W_0 - S^M$, $a_{22} = U_2(s_2^{AP}, s_1^{NI}, s_3^{NP}) = \pi_0 + \pi - W_0 - W - S^M$. Whether businesses should take active prevention depends on which option maximizes their net utility. The utility of businesses are higher in choosing to fight the epidemic when both other players choose to fight the epidemic, we assume that $a_{28} = U_2(s_2^{NP}, s_1^{NI}, s_3^{NP}) > a_{22} = U_2(s_2^{AP}, s_1^{NI}, s_3^{NP})$ and $a_{15} = U_2(s_2^{AP}, s_1^I, s_3^{AP}) > a_{111} = U_2(s_2^{NP}, s_1^I, s_3^{AP})$.

We assume that $z \in [0, 1]$ probability of businesses choosing active prevention with the government and $1 - z$ probability of the businesses choosing negative prevention. Table 2 shows the parameter description.

4. Model Analysis and Implications

4.1. Evolutionary stable strategy analysis

The average net payoff when the government chooses to implement strict restrictive policies is given by π_1^I. When government does not impose strict policies, the average net payoff is given by π_1^{NI}. The total average net payoff to government is $\bar{\pi}_1$.

$$\pi_1^I = y(1-z)a_{11} + yza_{14} + (1-y)(1-z)a_{17} + (1-y)za_{110}$$

$$\pi_1^{NI} = y(1-z)a_{21} + yza_{24} + (1-y)(1-z)a_{27} + (1-y)za_{210}$$

Table 2
The description of the parameters

Parameters	Description
$u_b \in \mathbb{R}_+$	Basic utility of the government
$\{R_M^j\}_{j=1}^{\infty} \subseteq \mathbb{R}_+$	Additional utility gained for the government from businesses
$\{R_C^{rj}\}_{j=1}^{\infty} \subseteq \mathbb{R}_-$	Additional utility gained for the government from freedom-centred consumers
$\{R_C^{aj}\}_{j=1}^{\infty} \subseteq \mathbb{R}_+$	Additional utility gained for the government from health-centred consumers
$c_0 \in \mathbb{R}_+$	Basic cost of the government if implementing strict restrictions
$\{c_i^G\}_{i \in N \setminus \{1\}} \in \mathbb{R}_+$	Additional cost for the government if businesses and consumers chooses negative prevention
$\{S_G^i\}_{i \in N \setminus \{1\}} \subseteq \mathbb{R}_+$	Subsidy for businesses and consumers from the government if implementing strict restrictions
$u_h \in \mathbb{R}_+$	Health utility of consumers
$u_o \in \mathbb{R}_+$	Other utility of consumers
$c_m^C \in \mathbb{R}_+$	Medical cost of consumers
$c_o^C \in \mathbb{R}_+$	Other consumption cost of consumers
$W_0 \in \mathbb{R}_+$	Basic wage of consumers
$W \in \mathbb{R}_+$	Performance wage of consumers
$\{c_p^i\}_{i \in N \setminus \{1\}} \in \mathbb{R}_+$	Punishment cost for consumers and businesses if the government implements strict restrictions while consumers and businesses taking negative prevention
$S^M \in \mathbb{R}_+$	Health subsidy gained for consumers from businesses if both businesses and consumers have active prevention actions
$\pi_0 \in \mathbb{R}_+$	Basic profit of businesses
$\pi \in \mathbb{R}_+$	Additional profit of businesses

$$\bar{\pi}_1 = x\pi_1^I + (1-x)\pi_1^{NI}$$
$$= x[y(1-z)a_{11} + yza_{14} + (1-y)(1-z)a_{17} + (1-y)za_{110}]$$
$$+ (1-x)[y(1-z)a_{21} + yza_{24} + (1-y)(1-z)a_{27} + (1-y)za_{210}]$$

$$\frac{dx}{dt} = x(\pi_1^I - \bar{\pi}_1) = x(1-x)[y(1-z)(a_{11} - a_{21}) + yz(a_{14} - a_{24}) + (1-y)(1-z)(a_{17} - a_{27}) + (1-y)z(a_{110} - a_{210})]$$

Let $F_1(x, y, z) = \frac{dx}{dt}$. We consider 2 situations of the dynamic progress of x. Situation 1: When $y = \frac{a_{27} - a_{17} - z(a_{110} - a_{210} - a_{17} + a_{27})}{a_{11} - a_{21} - a_{17} + a_{27} + z(a_{17} - a_{27} + a_{14} - a_{24} - a_{11} + a_{21} - a_{110} + a_{210})}$, $F_1(x, y, z) \equiv 0$. Situation 1 means $\forall (x, y, z) \in \{\Delta S_i\}_{i \in N}$ is an evolutionary stable point, that is, whether the government chooses to enforce strict restrictions or not, the government's strategy will not change over time. Situation 2: When $y \neq \frac{a_{27} - a_{17} - z(a_{110} - a_{210} - a_{17} + a_{27})}{a_{11} - a_{21} - a_{17} + a_{27} + z(a_{17} - a_{27} + a_{14} - a_{24} - a_{11} + a_{21} - a_{110} + a_{210})}$, let $F_1(x, y, z) = 0$, we can have $x = 0$ or $x = 1$. To further analyze the evolutionary stable strategy, we go further with $F_1(x, y, z)$ as follows:

$$\frac{\partial F_1(x, y, z)}{\partial x} = [y(1-z)(a_{11} - a_{21}) + yz(a_{14} - a_{24}) + (1-y)(1-z)(a_{17} - a_{27}) + (1-y)z(a_{110} - a_{210})](1 - 2x)$$

When $y < \frac{a_{27} - a_{17} - z(a_{110} - a_{210} - a_{17} + a_{27})}{a_{11} - a_{21} - a_{17} + a_{27} + z(a_{17} - a_{27} + a_{14} - a_{24} - a_{11} + a_{21} - a_{110} + a_{210})}$, $\frac{\partial F_1(x, y, z)}{\partial x}\big|_{x=0} < 0$, $\frac{\partial F_1(x, y, z)}{\partial x}\big|_{x=1} > 0$, thus, $x = 0$ is an evolutionary stable point, namely, the government will ultimately choose not to impose strict restrictions.

When $y > \frac{a_{27} - a_{17} - z(a_{110} - a_{210} - a_{17} + a_{27})}{a_{11} - a_{21} - a_{17} + a_{27} + z(a_{17} - a_{27} + a_{14} - a_{24} - a_{11} + a_{21} - a_{110} + a_{210})}$, $\frac{\partial F_1(x, y, z)}{\partial x}\big|_{x=0} > 0$, $\frac{\partial F_1(x, y, z)}{\partial x}\big|_{x=1} < 0$, thus, $x = 1$ is an evolutionary stable point, namely, the government will ultimately choose to impose strict restrictions. We analyze y in detail in section 4.

When the businesses choose to fight the pandemic with the government, the utility π_2^C denotes the average payoff, π_2^{NC} denotes the average payoff when the businesses choose not to fight the pandemic with the government and $\bar{\pi}_2$ denotes the total average payoff of the businesses.

$$\pi_2^C = x(1-z)a_{12} + xza_{15} + (1-x)(1-z)a_{22} + (1-x)za_{25}$$

$$\pi_2^{NC} = x(1-z)a_{18} + xza_{111} + (1-x)(1-z)a_{28} + (1-x)za_{211}$$

$$\bar{\pi}_2 = y\pi_2^C + (1-y)\pi_2^{NC}$$
$$= yx(1-z)a_{12} + yxza_{15} + y(1-x)(1-z)a_{22} + (1-x)zya_{25}$$
$$+ (1-y)x(1-z)a_{18} + (1-y)xza_{111} + (1-y)(1-x)(1-z)a_{28}$$
$$+ (1-y)(1-x)za_{211}$$

$$\frac{dy}{dt} = y(\pi_2^C - \bar{\pi}_2) = y(1-y)[x(1-z)(a_{12} - a_{18}) + xz(a_{15} - a_{111}) + (1-x)(1-z)(a_{22} - a_{28}) + (1-x)z(a_{25} - a_{211})]$$

Let $F_2(x, y, z) = \frac{dy}{dt}$, we discuss 2 situations of the dynamic progress of y. Situation 1: When $z = \frac{a_{28} - a_{25} - x(a_{12} - a_{18} - a_{22} + a_{28})}{x(a_{15} - a_{111} + a_{22} - a_{28} - a_{25} + a_{211}) + a_{25} - a_{211} - a_{12} + a_{18} - a_{22} + a_{28}}$, $F_2(x, y, z) \equiv 0$. Situation 1 means $\forall (x, y, z) \in \{\Delta S_i\}_{i \in N}$ is an evolutionary stable point, that is, whether the government / consumers choose to enforce strict restrictions / cooperate or not, the businesses' strategy will not change over time. Situation 2: When $z \neq \frac{a_{28} - a_{25} - x(a_{12} - a_{18} - a_{22} + a_{28})}{x(a_{15} - a_{111} + a_{22} - a_{28} - a_{25} + a_{211}) + a_{25} - a_{211} - a_{12} + a_{18} - a_{22} + a_{28}}$, let $F_2(x, y, z) = 0$, we can have $y = 0$ or $y = 1$. To further analyze the evolutionary stability strategy, we go further with $F_2(y)$ as follows:

$$\frac{\partial F_2(x, y, z)}{\partial y} = [x(1-z)(a_{12} - a_{18}) + xz(a_{15} - a_{111}) + (1-x)(1-z)(a_{22} - a_{28}) + (1-x)z(a_{25} - a_{211})](1 - 2y)$$

When $z < \frac{a_{28} - a_{25} - x(a_{12} - a_{18} - a_{22} + a_{28})}{x(a_{15} - a_{111} + a_{22} - a_{28} - a_{25} + a_{211}) + a_{25} - a_{211} - a_{12} + a_{18} - a_{22} + a_{28}}$, $\frac{\partial F_2(x, y, z)}{\partial y}\big|_{y=0} < 0$, $\frac{\partial F_2(x, y, z)}{\partial y}\big|_{y=1} > 0$, thus, $y = 0$ is an evolutionary stable point, namely, the government will ultimately choose not to impose strict restrictions.

When $z > \frac{a_{28}-a_{25}-x(a_{12}-a_{18}-a_{22}+a_{28})}{x(a_{15}-a_{111}+a_{22}-a_{28}-a_{25}+a_{211})+a_{25}-a_{211}-a_{12}+a_{18}-a_{22}+a_{28}}$, $\frac{\partial F_2(x,\ y,\ z)}{\partial y}|_{y=0}$
> 0, $\frac{\partial F_2(x,\ y,\ z)}{\partial y}|_{y=1} < 0$, thus, $y = 1$ is an evolutionary stable point, namely, the government will ultimately choose to impose strict restrictions. We will analyze y in detail in section 4.

When the consumers choose active prevention with the government, the utility π_3^C denotes the average payoff, π_3^{NC} denotes the average payoff when the consumers choose not to cooperate with the government and $\bar{\pi}_3$ denotes the total average payoff of the consumers.

$\pi_3^C = xya_{16} + x(1-y)a_{112} + (1-x)ya_{26} + (1-x)(1-y)a_{212}$

$\pi_3^{NC} = xya_{13} + x(1-y)a_{19} + (1-x)ya_{23} + (1-x)(1-y)a_{29}$

$\bar{\pi}_3 = z\pi_3^C + (1-z)\pi_3^{NC}$
$= xyza_{16} + xz(1-y)a_{112} + (1-x)yza_{26} + (1-x)(1-y)za_{212}$
$\quad + (1-z)xya_{13} + x(1-y)(1-z)a_{19} + (1-z)(1-x)ya_{23}$
$\quad + (1-z)(1-x)(1-y)a_{29}$

$\frac{dz}{dt} = z(\pi_3^C - \bar{\pi}_3) = z(1-z)[xy(a_{16}-a_{13}) + x(1-y)(a_{112}-a_{19})$
$\quad + (1-x)y(a_{26}-a_{23})$
$\quad + (1-x)(1-y)(a_{212}-a_{29})]$

Let $F_3(x, y, z) = \frac{dz}{dt}$, we discuss 2 situations of the dynamic progress of z. Situation 1: When $x = \frac{a_{29}-a_{212}-y(a_{16}-a_{13}+\ a_{26}-a_{23}-a_{112}+a_{19}-a_{212}+a_{29})}{a_{112}-a_{19}-y(\ a_{26}-a_{23}-a_{212}+\ a_{29})}$, $F_3(x, y, z) \equiv 0$. Situation 1 means $\forall (x, y, z) \in \{\Delta S_i\}_{i \in N}$ is an evolutionary stable point, that is, whether the businesses / the government choose to cooperate / enforce strict restrictions or not, the consumers' strategy will not change over time. Situation 2: When $x \neq \frac{a_{29}-a_{212}-y(a_{16}-a_{13}+\ a_{26}-a_{23}-a_{112}+a_{19}-a_{212}+a_{29})}{a_{112}-a_{19}-y(\ a_{26}-a_{23}-a_{212}+\ a_{29})}$, let $F_3(x, y, z) = 0$, we can have $z = 0$ or $z = 1$.

To further analyze the evolutionary stability strategy, we go further with $F_3(z)$ as follows:

$\frac{\partial F_3(x,\ y,\ z)}{\partial z} = [xy(a_{16}-a_{13}) + x(1-y)(a_{112}-a_{19}) + (1-x)y(a_{26}-a_{23})$
$\quad + (1-x)(1-y)(a_{212}-a_{29})](1-2z)$

When $x < \frac{a_{29}-a_{212}-y(a_{16}-a_{13}+\ a_{26}-a_{23}-a_{112}+a_{19}-a_{212}+a_{29})}{a_{112}-a_{19}-y(\ a_{26}-a_{23}-a_{212}+\ a_{29})}$, $\frac{\partial F_3(x,\ y,\ z)}{\partial z}|_{z=0} < 0$, $\frac{\partial F_3(x,\ y,\ z)}{\partial z}|_{z=1} > 0$, thus, $z = 0$ is an evolutionary stable point, namely, the government will ultimately choose not to impose strict restrictions.

When $x > \frac{a_{29}-a_{212}-y(a_{16}-a_{13}+\ a_{26}-a_{23}-a_{112}+a_{19}-a_{212}+a_{29})}{a_{112}-a_{19}-y(\ a_{26}-a_{23}-a_{212}+\ a_{29})}$, $\frac{\partial F_3(x,\ y,\ z)}{\partial z}|_{z=0} > 0$, $\frac{\partial F_3(x,\ y,\ z)}{\partial z}|_{z=1} < 0$, thus, $z = 1$ is an evolutionary stable point, namely, the government will ultimately choose to impose strict restrictions. We will analyze y in detail in section 4.

Based on the assumption 1, 2 and 3, we can solve x, y and z equations:

to find a unique saddle point (x^*, y^*, z^*).

Lemma: There are eight possible evolutionary stable strategy: $(0, 0, 0)$, $(0, 0, 1)$, $(0, 1, 0)$, $(0, 1, 1)$, $(1, 0, 0)$, $(1, 0, 1)$, $(1, 1, 0)$, $(1, 1, 1)$, if and only if each point satisfies corresponding eigenvalues less than 0.

According to the Lyapunov stability analysis, we only need to prove the eigenvalues less than 0 in the Jacobian matrix. There are eight stable points: $(0, 0, 0)$, $(0, 0, 1)$, $(0, 1, 0)$, $(0, 1, 1)$, $(1, 0, 0)$, $(1, 0, 1)$, $(1, 1, 0)$, $(1, 1, 1)$,. The saddle point is $x = \frac{a_{29}-a_{212}-y(a_{16}-a_{13}+\ a_{26}-a_{23}-a_{112}+a_{19}-a_{212}+a_{29})}{a_{112}-a_{19}-y(\ a_{26}-a_{23}-a_{212}+\ a_{29})}$, $y = \frac{a_{27}-a_{17}-z(a_{110}-a_{210}-a_{17}+a_{27})}{a_{11}-a_{21}-a_{17}+a_{27}+z(a_{17}-a_{27}+a_{14}-a_{24}-a_{11}+a_{21}-a_{110}+a_{210})}$ and $z = \frac{a_{28}-a_{25}-x(a_{12}-a_{18}-a_{22}+a_{28})}{x(a_{15}-a_{111}+a_{22}-a_{28}-a_{25}+a_{211})+a_{25}-a_{211}-a_{12}+a_{18}-a_{22}+a_{28}}$. The Jacobi Matrix is calculated to assess the stability of the equilibrium point.

$$J = \begin{pmatrix} \frac{\partial F_1(x,\ y,\ z)}{\partial x} & \frac{\partial F_1(x,\ y,\ z)}{\partial y} & \frac{\partial F_1(x,\ y,\ z)}{\partial z} \\ \frac{\partial F_2(x,\ y,\ z)}{\partial x} & \frac{\partial F_2(x,\ y,\ z)}{\partial y} & \frac{\partial F_2(x,\ y,\ z)}{\partial z} \\ \frac{\partial F_3(x,\ y,\ z)}{\partial x} & \frac{\partial F_3(x,\ y,\ z)}{\partial y} & \frac{\partial F_3(x,\ y,\ z)}{\partial z} \end{pmatrix} = \begin{pmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{pmatrix}$$

Where $b_{11} = \frac{\partial F_1(x,\ y,\ z)}{\partial x} = [y(1-z)(a_{11}-a_{21}) + yz(a_{14}-a_{24}) + (1-y)(1-z)(a_{17}-a_{27}) + (1-y)z(a_{110}-a_{210})](1-2x)$, $b_{12} = \frac{\partial F_1(x,\ y,\ z)}{\partial y} = x(1-x)[(a_{11}-a_{21})(1-z) + z(a_{14}-a_{24}) + (z-1)(a_{17}-a_{27}) - z(a_{110}-a_{210})]$, $b_{13} = \frac{\partial F_1(x,\ y,\ z)}{\partial z} = x(1-x)[-y(a_{11}-a_{21}) + y(a_{14}-a_{24}) + (y-1)(a_{17}-a_{27}) + (1-y)(a_{110}-a_{210})]$; $b_{21} = \frac{\partial F_2(x,\ y,\ z)}{\partial x} = y(1-y)[(1-z)(a_{12}-a_{18}) + z(a_{15}-a_{111}) + (z-1)(a_{22}-a_{28}) - z(a_{25}-a_{211})]$, $b_{22} = \frac{\partial F_2(x,\ y,\ z)}{\partial y} = [x(1-z)(a_{12}-a_{18}) + xz(a_{15}-a_{111}) + (1-x)(1-z)(a_{22}-a_{28}) + (1-x)z(a_{25}-a_{211})](1-2y)$, $b_{23} = \frac{\partial F_2(x,\ y,\ z)}{\partial z} = y(1-y)[-x(a_{12}-a_{18}) + x(a_{15}-a_{111}) + (x-1)(a_{22}-a_{28}) + (1-x)(a_{25}-a_{211})]$; $b_{31} = \frac{\partial F_3(x,\ y,\ z)}{\partial x} = z(1-z)[y(a_{16}-a_{13}) + (1-y)(a_{112}-a_{19}) - y(a_{26}-a_{23}) + (y-1)(a_{212}-a_{29})]$, $b_{32} = \frac{\partial F_3(x,\ y,\ z)}{\partial x} = z(1-z)[x(a_{16}-a_{13}) - x(a_{112}-a_{19}) + (1-x)(a_{26}-a_{23}) + (x-1)(a_{212}-a_{29})]$, $b_{33} = \frac{\partial F_3(x,\ y,\ z)}{\partial x} = [xy(a_{16}-a_{13}) + x(1-y)(a_{112}-a_{19}) + (1-x)y(a_{26}-a_{23}) + (1-x)(1-y)(a_{212}-a_{29})](1-2z)$.

The equilibrium points $(0, 0, 0), (0, 0, 1)\ (0, 1, 0), (0, 1, 1)$ are substituted into the Jacobian matrix:

For point $(0, 0, 0)$: $\det J = (a_{17}-a_{27})(a_{22}-a_{28})(a_{212}-a_{29})$; $tr\ J = a_{17}-a_{27}+a_{22}-a_{28}+a_{212}-a_{29}$. The corresponding matrix is:
$$\begin{pmatrix} a_{17}-a_{27} & 0 & 0 \\ 0 & a_{22}-a_{28} & 0 \\ 0 & 0 & a_{212}-a_{29} \end{pmatrix}.$$

For point $(0, 0, 1)$: $\det J = (a_{110}-a_{210})(a_{25}-a_{211})(a_{212}-a_{29})$; $tr\ J = a_{110}-a_{210}+a_{25}-a_{211}+a_{212}-a_{29}$. The corresponding matrix is:
$$\begin{pmatrix} a_{110}-a_{210} & 0 & 0 \\ 0 & a_{25}-a_{211} & 0 \\ 0 & 0 & a_{212}-a_{29} \end{pmatrix}.$$

For point $(0, 1, 0)$: $\det J = (a_{11}-a_{21})(a_{22}-a_{28})(a_{26}-a_{23})$; $tr\ J =$

$$\begin{cases} x = \dfrac{u_o + W_0 + W - c_m^C - u_h - 2yW_0}{u_h + S_G^C - u_o - W_0 - W + c_m^C + c_p^C - yW_0} \\[4mm] y = \dfrac{-c_p^C - c_p^M + c_0 + R_M + R_C^r - z\left(u_b + 3R_C^a - S_G^C - c_M^C - c_p^C + R_M\right)}{u_b + 2R_M + c_p^C - S_G^M - c_0 - c_c^C - R_C^r - c_p^C - c_p^M + c_0 + R_M + R_C^r + z\left(+ c_c^C - u_b + c_M^G - R_M\right)} \\[4mm] z = \dfrac{\pi - W + S^M - xc_m^M}{x\left(c_p^M - S^M\right) - c_p^M + S^M} \end{cases}$$

$a_{11} - a_{21} + a_{22} - a_{28} + a_{26} - a_{23}$. The corresponding matrix is:

$$\begin{pmatrix} a_{11} - a_{21} & 0 & 0 \\ 0 & a_{22} - a_{28} & 0 \\ 0 & 0 & a_{26} - a_{23} \end{pmatrix}.$$

For point $(0, 1, 1)$: $\det J = (a_{14} - a_{24})(a_{25} - a_{211})(a_{26} - a_{23})$; $tr\ J = a_{14} - a_{24} + a_{211} - a_{25} + a_{26} - a_{23}$. The corresponding matrix is:

$$\begin{pmatrix} a_{14} - a_{24} & 0 & 0 \\ 0 & a_{25} - a_{211} & 0 \\ 0 & 0 & a_{26} - a_{23} \end{pmatrix}.$$

The equilibrium points $(1, 0, 0)$, $(1, 0, 1)$, $(1, 1, 0)$, $(1, 1, 1)$ are substituted into the Jacobian matrix:

For point $(1, 0, 0)$: $\det J = (a_{17} - a_{27})(a_{12} - a_{18})(a_{112} - a_{19})$; $tr\ J = a_{17} - a_{27} + a_{12} - a_{18} + a_{112} - a_{19}$. The corresponding matrix is:

$$\begin{pmatrix} a_{17} - a_{27} & 0 & 0 \\ 0 & a_{12} - a_{18} & 0 \\ 0 & 0 & a_{112} - a_{19} \end{pmatrix}.$$

For point $(1, 0, 1)$: $\det J = (a_{110} - a_{210})(a_{15} - a_{111})(a_{112} - a_{19})$; $tr\ J = a_{110} - a_{210} + a_{15} - a_{111} + a_{112} - a_{19}$. The corresponding matrix is:

$$\begin{pmatrix} a_{110} - a_{210} & 0 & 0 \\ 0 & a_{15} - a_{111} & 0 \\ 0 & 0 & a_{112} - a_{19} \end{pmatrix}.$$

For point $(1, 1, 0)$: $\det J = (a_{11} - a_{21})(a_{12} - a_{18})(a_{16} - a_{13})$; $tr\ J = a_{11} - a_{21} + a_{12} - a_{18} + a_{16} - a_{13}$. The corresponding matrix is:

$$\begin{pmatrix} a_{11} - a_{21} & 0 & 0 \\ 0 & a_{12} - a_{18} & 0 \\ 0 & 0 & a_{16} - a_{13} \end{pmatrix}.$$

For point $(1, 1, 1)$: $\det J = (a_{14} - a_{24})(a_{15} - a_{111})(a_{16} - a_{13})$; $tr\ J = a_{14} - a_{24} + a_{15} - a_{111} + a_{16} - a_{13}$. The corresponding matrix is:

$$\begin{pmatrix} a_{14} - a_{24} & 0 & 0 \\ 0 & a_{15} - a_{111} & 0 \\ 0 & 0 & a_{16} - a_{13} \end{pmatrix}.$$

Our analysis of the eigenvalues of the Jacobian at each point in Table 3 is equivalent to the analysis of the determinant values and traces of their respective Jacobian matrices. The evolutionary stable points require that the determinant of the Jacobian matrix be less than 0 and the trace is greater than 0. Table 3 summarizes the determinant values and traces of all equilibrium points in Jacobian matrices.

We first describe the replicate dynamic trajectories of the saddle points. The dynamic trajectory will show the direction of motion of the midpoint in different regions, which is of great significance when analyzing the phase diagram later. Similarly, we analyze the Jacobian matrix eigenvalues of each point in Table 2 to judge the existence of ESS points. Fig. 1, Fig. 2, and Fig. 3 illustrate the dynamic process of saddle point replication. The solid arrow line represents convergence to 1, and the dashed arrow line represents convergence to 0

Table 3 describes the equilibrium points that may become evolutionarily stable strategies. We divide the space into 8 regions with (x^*, y^*, z^*) as the center: I, II, III, IV, V, VI, VII and VIII. Fig. 4 reflects the 8 regions in the space. Table 4 shows the subspace names that each region represent.

We will use propositions 1 to 4 to answer the two research questions of this paper. Figs. 5–8 shows the dynamic trajectory when the initial point is in region III, V (Hexahedron *FGHIPKLO*), II (Pentahedron

Table 3
Equilibrium points

Points	tr	det
$(0, 0, 0)$	$a_{17} - a_{27} + a_{22} - a_{28} + a_{212} - a_{29}$	$(a_{17} - a_{27})(a_{22} - a_{28})(a_{212} - a_{29})$
$(0, 0, 1)$	$a_{110} - a_{210} + a_{25} - a_{211} + a_{29} - a_{212}$	$(a_{110} - a_{210})(a_{25} - a_{211})(a_{29} - a_{212})$
$(0, 1, 0)$	$a_{11} - a_{21} + a_{28} - a_{22} + a_{26} - a_{23}$	$(a_{11} - a_{21})(a_{28} - a_{22})(a_{26} - a_{23})$
$(0, 1, 1)$	$a_{14} - a_{24} + a_{211} - a_{25} + a_{23} - a_{26}$	$(a_{14} - a_{24})(a_{211} - a_{25})(a_{23} - a_{26})$
$(1, 0, 0)$	$a_{27} - a_{17} + a_{12} - a_{18} + a_{112} - a_{19}$	$(a_{27} - a_{17})(a_{12} - a_{18})(a_{112} - a_{19})$
$(1, 0, 1)$	$a_{210} - a_{110} + a_{15} - a_{111} + a_{19} - a_{112}$	$(a_{210} - a_{110})(a_{15} - a_{111})(a_{19} - a_{112})$
$(1, 1, 0)$	$a_{21} - a_{11} + a_{18} - a_{12} + a_{16} - a_{13}$	$(a_{21} - a_{11})(a_{18} - a_{12})(a_{16} - a_{13})$
$(1, 1, 1)$	$a_{24} - a_{14} + a_{111} - a_{15} + a_{13} - a_{16}$	$(a_{24} - a_{14})(a_{111} - a_{15})(a_{13} - a_{16})$

BETRHG) and VIII (Pentahedron *IHKPNJ*), respectively. The solid green line shows the direction of force, and the dotted green line shows the direction of final movement in Figs. 5–8. We first analyze the replicate dynamic process when the initial point is in region III (Pentahedron *SEHIJD*).

Proposition 1. If the position of the initial point is in region III (Pentahedron *SEHIJD*), namely, $x \in (x^*, 1)$, $y \in (0, y^*)$ and $z \in (z^*, 1)$, (x, y, z) will convergence to the point $(1, 0, 0)$. $(1, 0, 0)$ will be the ESS, if it satisfied the following two conditions:

$$\begin{cases} c_p^C + c_p^M \in [0,\ c_0 + R_M + R_C^r) \\ c_p^C + S_G^C \in [0,\ u_o + W_0 + W - c_m^C - u_h) \\ c_p^M \in [0,\ S^M) \end{cases}$$

See Appendix A.1 for the proof of proposition 1

Proposition 2. If the position of the initial point is in region V (Hexahedron *FGHIPKLO*), namely, $x \in (0, x^*)$, $y \in (0, 1)$ and $z \in (0, z^*)$, (x, y, z) will convergence to the point $(0, 1, 0)$. $(0, 1, 0)$ will be the ESS, if it satisfied the following two conditions:

$$\begin{cases} S_G^M - c_p^C > u_b + 2R_M - c_0 - c_c^G - R_C^r \\ u_h - u_o - W + c_m^C < 0 \end{cases}.$$

See Appendix A.2 for the proof of proposition 2

Proposition 3. If the position of the initial point is in region II (Pentahedron *BETRHG*), namely, $x \in (0, x^*)$, $y \in (y^*, 1)$ and $z \in (z^*, 1)$, (x, y, z) will convergence to the point $(1, 1, 1)$. $(1, 1, 1)$ will be the

ESS, if it satisfied the condition: $\begin{cases} S_G^M + S_G^C \in [0,\ u_b + 2R_M + 2R_C^a - c_0) \\ c_p^M \in (S^M,\ +\infty) \\ S_G^C + c_p^C \in (u_o + W - c_m^C - u_h,\ +\infty) \end{cases}.$

See Appendix A.3 for the proof of proposition 3

Proposition 4. If the position of the initial point is in region VIII (Pentahedron *IHKPNJ*), namely, $x \in (x^*, 1)$, $y \in (0, y^*)$ and $z \in (0, z^*)$, (x, y, z) will convergence to the point $(0, 0, 0)$. $(0, 0, 0)$ will be the

ESS, if it satisfied the condition: $\begin{cases} c_p^C + c_p^M \in [0,\ c_0 + R_M + R_C^r) \\ u_h - u_o - W_0 - W + c_m^C < 0 \end{cases}.$

See Appendix A.4 for the proof of proposition 4

Proposition 5. $(0, 0, 1)$, $(0, 1, 1)$, $(1, 0, 1)$, $(1, 1, 0)$ and $(0, 1, 1)$ are not the ESS point.

See Appendix A.5 for the proof of proposition 5

To sum up, we conclude four ESS points: $(1, 1, 1)$, $(0, 1, 0)$, $(0, 0, 0)$, $(1, 0, 0)$. By establishing propositions 1-3, we have answered the first research questions: In the long term, there are four equilibrium strategy profiles can be chosen for the government, businesses, and consumers to meet their respective utility maximization. The dynamic process of the above four points answers the first research question of this paper.

We also have answered the second research question in this paper according to propositions 1 to 3. Different convergence points correspond to different subsidy and penalty mechanisms, namely, if these corresponding subsidy-penalty mechanisms are satisfied, the corresponding final combination of strategies will be realized. We summarize those subsidy-penalty mechanisms as follows: If the government, businesses, and consumers choose $(0, 1, 0)$ as the final probability of strategy profile, the subsidy-punishment mechanism is as follows:

$$\begin{cases} S_G^M - c_p^C > u_b + 2R_M - c_0 - c_c^G - R_C^r \\ u_h - u_o - W + c_m^C < 0 \end{cases}.$$ If the government, businesses,

and consumers choose $(1, 0, 0)$ as the final probability of strategy
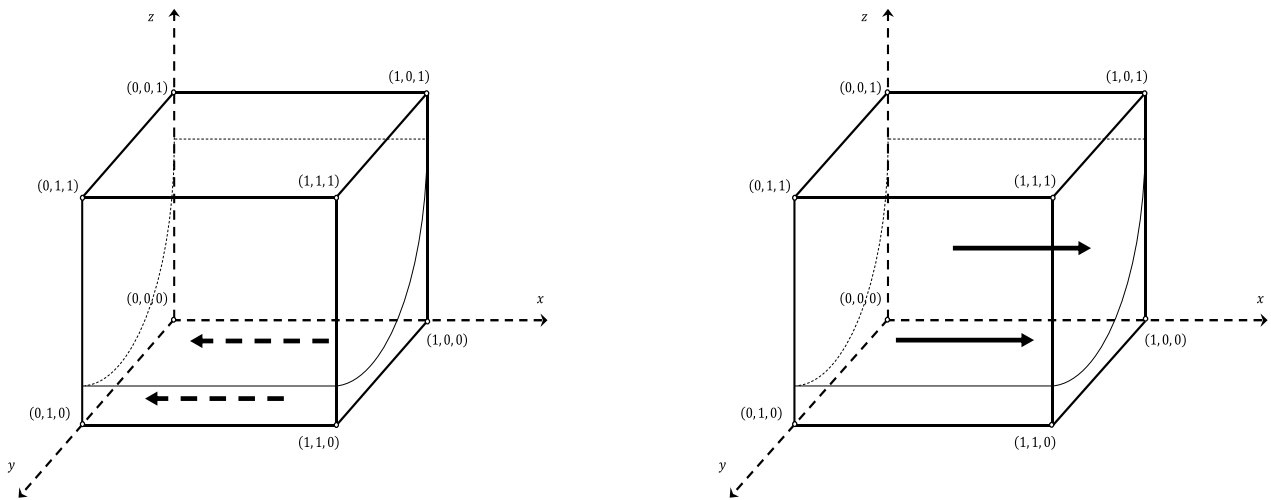
Fig. 1. When $y \neq \frac{a_{27}-a_{17}-z(a_{110}-a_{210}-a_{17}+a_{27})}{a_{11}-a_{21}-a_{17}+a_{27}+z(a_{17}-a_{27}+a_{14}-a_{24}-a_{11}+a_{21}-a_{110}+a_{210})}$, replicate dynamic trajectories of *x*.
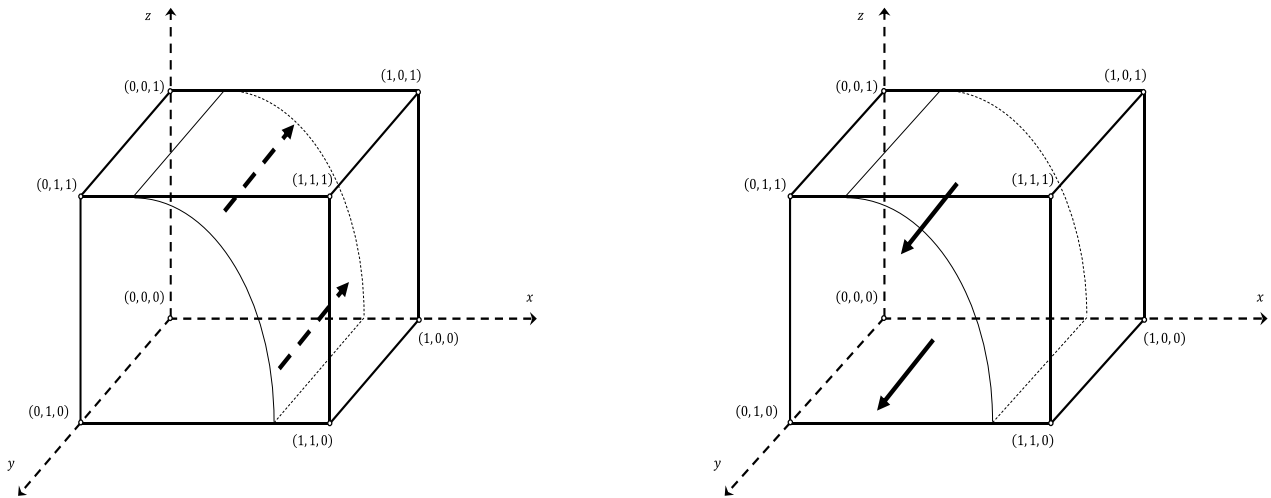

Fig. 2. When $z \neq \frac{a_{28}-a_{25}-x(a_{12}-a_{18}-a_{22}+a_{28})}{x(a_{15}-a_{111}+a_{22}-a_{28}-a_{25}+a_{211})+a_{25}-a_{211}-a_{12}+a_{18}-a_{22}+a_{28}}$, replicate dynamic trajectories of *y*
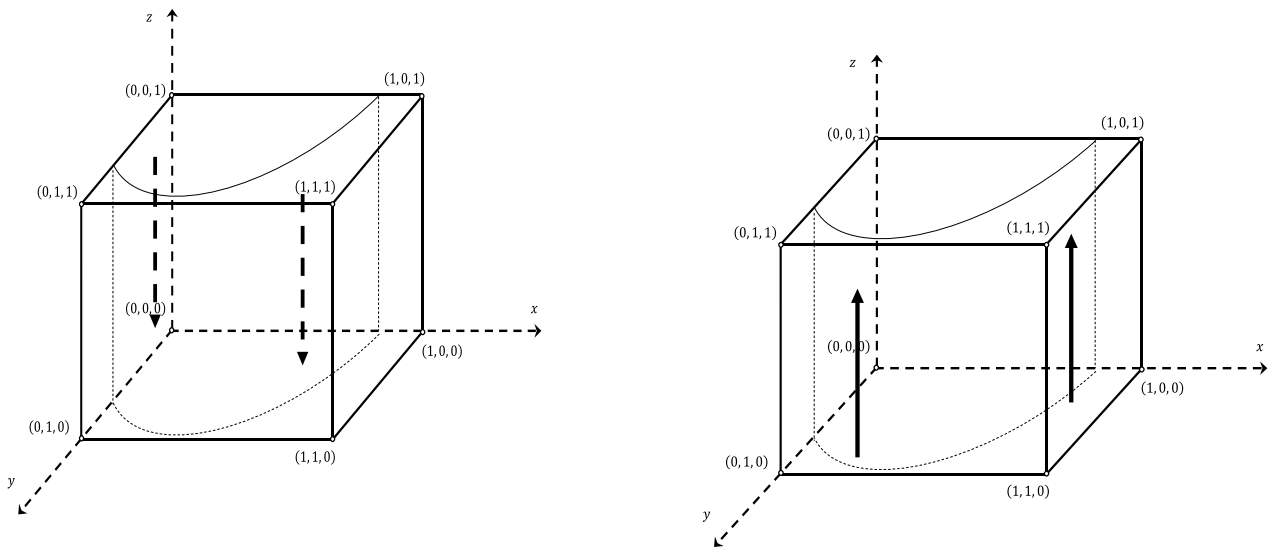

Fig. 3. When $x \neq \frac{a_{29}-a_{212}-y(a_{16}-a_{13}+a_{26}-a_{23}-a_{112}+a_{19}-a_{212}+a_{29})}{a_{112}-a_{19}-y(a_{26}-a_{23}-a_{212}+a_{29})}$, replicate dynamic trajectories of *z*.
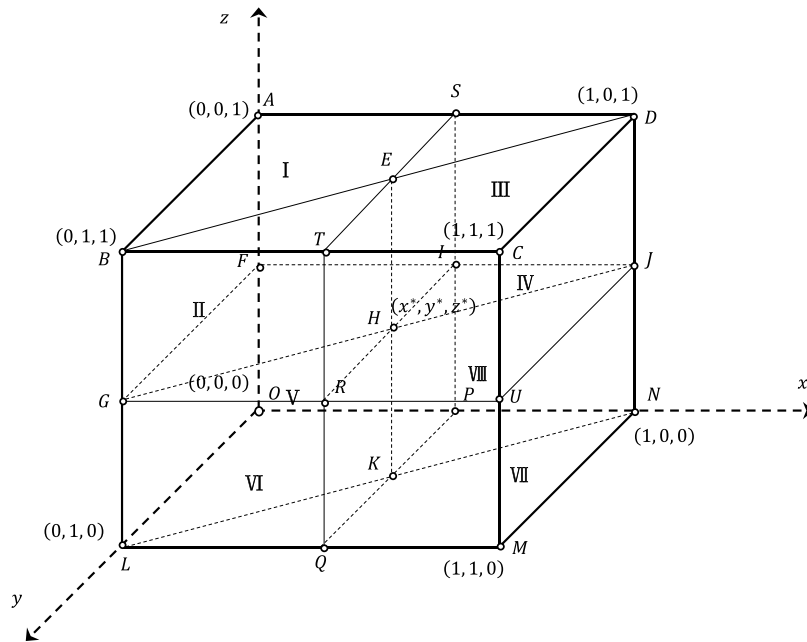
Fig. 4. Eight different subspaces.

Table 4
Subspace description of each region.

Region	Subspace description
I	Hexahedron *ABESIHGF*
II	Pentahedron *BETRHG*
III	Pentahedron *SEHIJD*
IV	Hexahedron *EDCTRUJH*
V	Hexahedron *FGHIPKLO*
VI	Pentahedron *GRHKQL*
VII	Hexahedron *HRUJNMQK*
VIII	Pentahedron *IHKPNJ*

profile, the subsidy-punishment mechanism is as follows:

$$\begin{cases} c_p^C + c_p^M \in [0, \ c_0 + R_M + R_C^r) \\ c_p^C + S_G^C \in [0, \ u_o + W_0 + W - c_m^C - u_h) . \text{ If the government, businesses,} \\ c_p^M \in [0, \ S^M) \end{cases}$$

and consumers choose $(1, 1, 1)$ as the final probability of strategy profile, the subsidy-punishment mechanism is as follows:

$$\begin{cases} S_G^M + S_G^C \in [0, \ u_b + 2R_M + 2R_C^a - c_0) \\ c_p^M \in (S^M, \ +\infty) \\ S_G^C + c_p^C \in (u_o + W - c_m^C - u_h, \ +\infty) \end{cases} . \text{ If the government, businesses,}$$

and consumers choose $(0, 0, 0)$ as the final probability of strategy profile, the subsidy-punishment mechanism is as follows:

$$\begin{cases} c_p^C + c_p^M \in [0, \ c_0 + R_M + R_C^r) \\ u_h - u_o - W_0 - W + c_m^C < 0 \end{cases} . \text{ We further integrate the above neces-}$$

sary conditions. One of the necessary conditions from proposition 3 requires $c_p^C + S_G^C \in [0, \ u_o + W_0 + W - c_m^C - u_h)$, which implies $u_o + W_0 + W - c_m^C - u_h \geq 0$. It is equivalent to the condition $u_h - u_o - W_0 - W + c_m^C \leq 0$.

There is a same necessary condition between proposition 1 and 4: $c_p^C + c_p^M \in [0, \ c_0 + R_M + R_C^r)$. If our parameter values satisfy the necessary conditions of proposition 4, it also satisfy the necessary conditions of proposition 1. Therefore, we believe that there is no $(1, 0, 0)$ in the real situation, that is, when the businesses and consumers give up to fight against the COVID-19, the government will ultimately give up. $(1, 0, 0)$

will change to $(0, 0, 0)$. These subsidy and punishment mechanisms influence the decisions of governments, businesses, and consumers through their range of values. If punishment is too low, businesses and consumers have no incentive to comply. Therefore, subsidy and punishment should be set within a reasonable range to effectively motivate businesses and consumers. High subsidies, however, weaken the incentive for the government to implement policies as these come with high fiscal cost. This is likely to be especially relevant to less developed countries. Table 5 shows the evolutionary stable strategy points. We believe that the theoretical analysis results reflect the government's policy thinking on punishment and subsidy. We will verify our above results by numerical analysis in the section 4.2.

4.2. Numerical analysis

We perform numerical analysis using Matlab on the above four ESS points. The purpose of our numerical simulation is to further verify whether our theoretical ESS points are correct.

Therefore, we design multi-class values. The first class is to examine the influence of subsidy and punishment mechanism on the decision-making of the government, businesses, and consumers when there is high subsidy for both businesses and consumers. Under the high subsidy mechanism, we want to test how changes in the punishment mechanism affect the decision of the three parties. The second class is to examine the influence of subsidy and punishment mechanism on the decision-making when there is low subsidy for both businesses and consumers. The third class is to test the influence of subsidy and punishment mechanism on the decision-making when there is low subsidy for consumers while high subsidy for businesses. The fourth class is to test the influence of subsidy and punishment mechanism on the decision-making when there is low subsidy for businesses while high subsidy for consumers.

According to the assumption, we randomly extract rational numbers from $(0, \ +\infty)$ and the numbers extracted cannot be special (such as the extreme point, the maximum point, etc.). These two principles guarantee the non-particularity of the other parameters. Except for the penalty and subsidy parameters, we set the rest of parameters strictly according to all the necessary conditions in our previous propositions. $u_b = 5; c_c^G = 1.5; R_C^r = 1.5; R_M = 2.5; R_C^a = 6; c_0 = 5; c_M^G = 1.5; S_M = 40; W = 2.5; u_h = 0.5; u_o = 32.5; c_m^C = 4.5; W_0 = 2$. Table 6 shows the
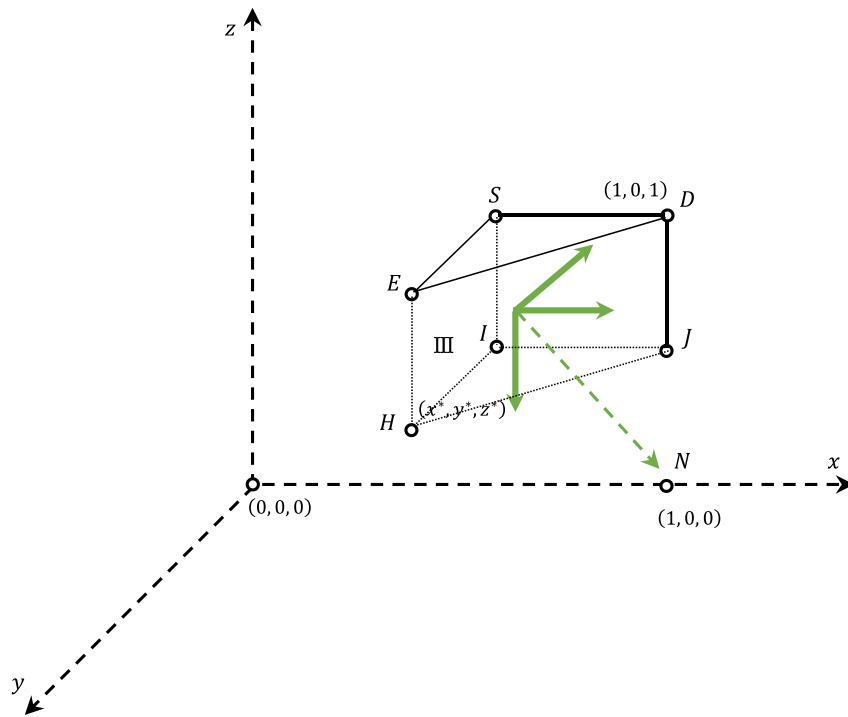
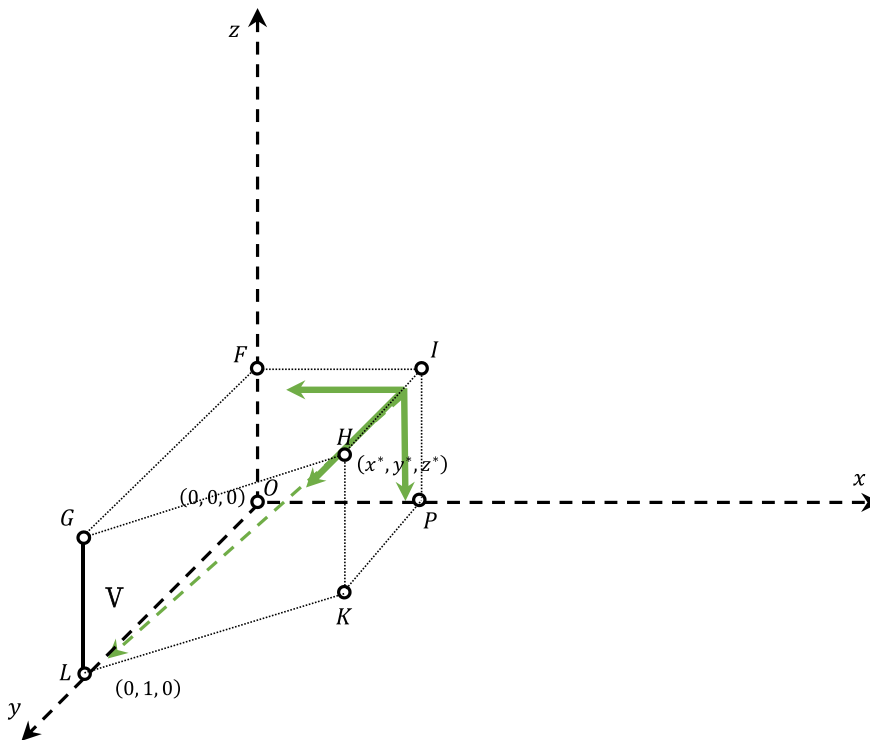**Fig. 5.** Dynamic trajectory when the initial point is in region III.

Fig. 6. Dynamic trajectory when the initial point is in region V.

values in our numerical experiment. The cases from first class to the fourth class in bold indicates that the final choice probability of the three parties can converge to 0 or 1.

Figs. 9(a), 9(b), 10(a), 10(b) show the dynamic process of three-dimensional tripartite evolutionary game and two-dimensional tripartite evolutionary game under the parameters of the first class to fourth class. We use "red dotted line" to represent the government, "green

dotted line" to represent consumers and "black dotted line" to represent businesses in Figs. 9(a), 9(b), 10(a), 10(b).

The numerical analysis results of four classes show that: first, the penalty mechanism is more important than the subsidy mechanism. The penalty mechanism determines the convergence of the final strategy choices of the government, businesses and consumers. It is the key to the whole analysis. Second, different participants had different sensitivities
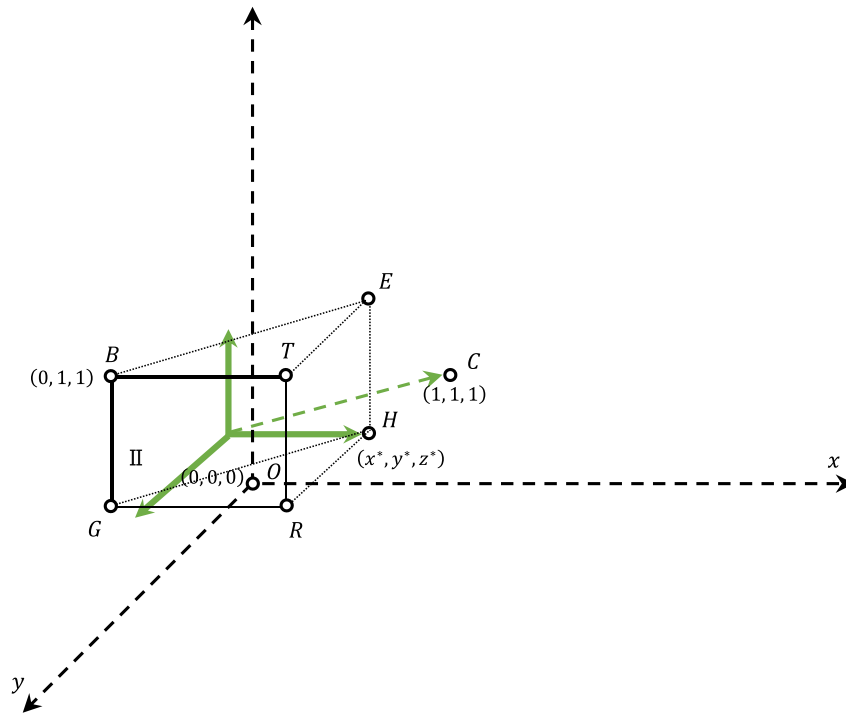
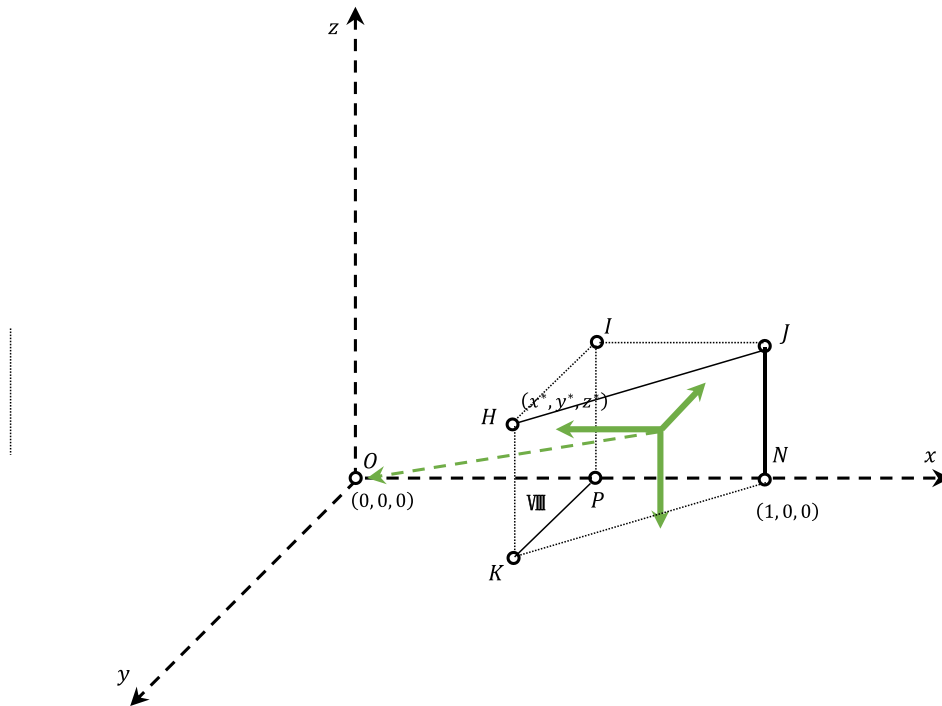**Fig. 7.** Dynamic trajectory when the initial point is in region II.

Fig. 8. Dynamic trajectory when the initial point is in region VIII.

to the punishment parameters. High penalties can give businesses and consumers high incentive to act against the epidemic. At the same time, the high penalty mechanism can provide high incentives for the government to choose to fight the COVID-19 due to increasing the government income. Therefore, when businesses and consumers are under the high penalty mechanism, the government, businesses and consumers can form a joint anti-epidemic group, that is, the ESS point of $(1, 1, 1)$ can be finally formed. In contrast, when the penalty is low, the gov-

ernment, businesses and consumers have little incentive to fight the COVID-19. Eventually, no matter what subsidy mechanism is given, the government, businesses and consumers all will choose to give up fighting the COVID-19, that is, the ESS point of $(0, 0, 0)$ can be formed. The third class represents the situation when the government gives high penalty to consumers and low penalty to businesses. The high penalty mechanism for consumers can give consumers enough incentive to fight the COVID-19. However, due to the low penalty mechanism of busi-

Table 5
Evolutionary stable strategy points

Points	ESS
(0, 0, 0)	ESS
(0, 0, 1)	/
(0, 1, 0)	ESS
(0, 1, 1)	/
(1, 0, 0)	ESS
(1, 0, 1)	/
(1, 1, 0)	/
(1, 1, 1)	ESS

Table 6
The setting of multi-class numerical simulation

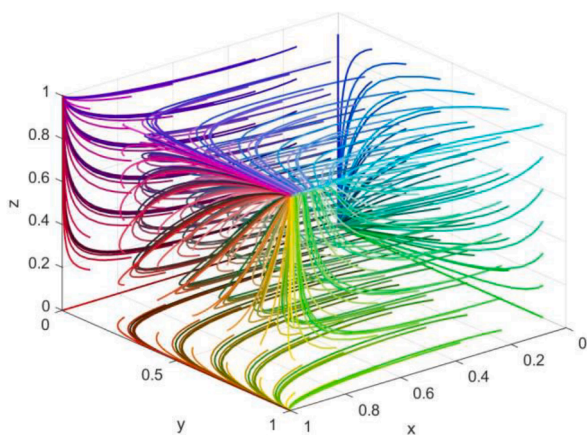| The first class				
Case	S_G^M	S_G^C	c_p^C	c_p^M
1	**2**	**2**	**100**	**100**
2	2	100	100	100
3	100	2	100	100
4	100	100	100	100
The second class				
Case	S_G^M	S_G^C	c_p^C	c_p^M
1	**2**	**2**	**2**	**2**
2	**2**	**100**	**2**	**2**
3	**100**	**2**	**2**	**2**
4	**100**	**100**	**2**	**2**
The third class				
Case	S_G^M	S_G^C	c_p^C	c_p^M
1	**2**	**2**	**100**	**2**
2	2	100	100	2
3	**100**	**2**	**100**	**2**
4	100	100	100	2
The fourth class				
Case	S_G^M	S_G^C	c_p^C	c_p^M
1	**2**	**2**	**2**	**100**
2	2	100	2	100
3	100	2	2	100
4	100	100	2	100

nesses, although the government can provide incentives for businesses to fight against the COVID-19 through the subsidy mechanism, once businesses participate in active prevention, they need to give consumers health subsidies. There is a trade-off between businesses' subsidies and government subsidies. Therefore, businesses cannot generate enough

incentives to fight the COVID-19, and (1, 0, 1) will be formed as an ESS point. The fourth class represents the situation when the government gives high penalty to businesses and low penalty to consumers. The high penalty for businesses gives them enough incentive to take the active prevention. However, because of the low penalty mechanism for consumers, consumers have no incentive to participate in taking active prevention. Thus, (1, 1, 0) will be formed as an ESS point. In both the third class and the fourth class, the government imposed heavy penalties on consumers or businesses. Therefore, governments always have an incentive to fight the COVID-19.

5. Conclusion and Discussion

We have answered two research questions for this paper. Through the solution of the evolutionary game model and numerical analysis, we find that there are four possible situations during COVID-19 in a country: 1. The government and businesses choose to actively prevent the COVID-19 together, and consumers do not support fighting the pandemic. 2. The government, businesses and consumers form a united front to fight the pandemic. 3. The government and consumers choose to actively prevent the COVID-19 together, and businesses do not support fighting the COVID-19. 4. All of the participants give up fighting against the COVID-19.

Our findings added more detailed results about the impact of punishment and subsidy mechanisms on decisions of the government, businesses, and consumers based on the Zhi, et al. [16]. In their article, they made some suggestive but imprecise conclusions. For example, "*As the manager and facilitator of epidemic prevention and control, the government should avoid taking too tough measures to avoid arousing opposition from the public and businesses*" (Zhi, et al, [16], p.13) and "*Local governments should work out different punishment and support mechanisms, not just punishment and subsidies. For example, once the bad behavior of enterprises is discovered, the local government should immediately deal with the offending enterprises. Local governments should pay high attention to the negative impact of the epidemic on enterprises' production and operation. While maintaining social security and stability, we should protect the interests of enterprises, pay attention to their production and operation, and understand the actual situation of enterprises*" (Zhi, et al, [16], p.13). These conclusions do not show in detail how the mechanism of penalties and subsidies works on businesses and consumers. Through our second research question: *How the penalty and subsidy mechanisms impact the resulting equilibria?* We show that the penalty mechanism is more
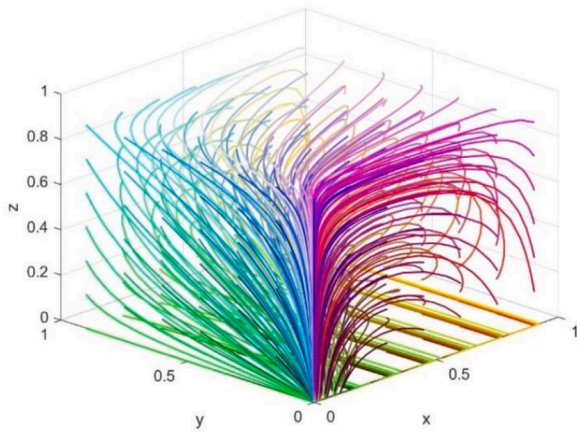

(a). Dynamic process of three-dimensional tripartite evolutionary game under the first class
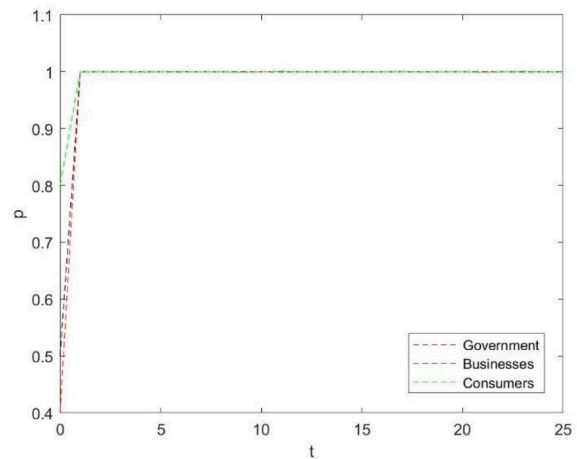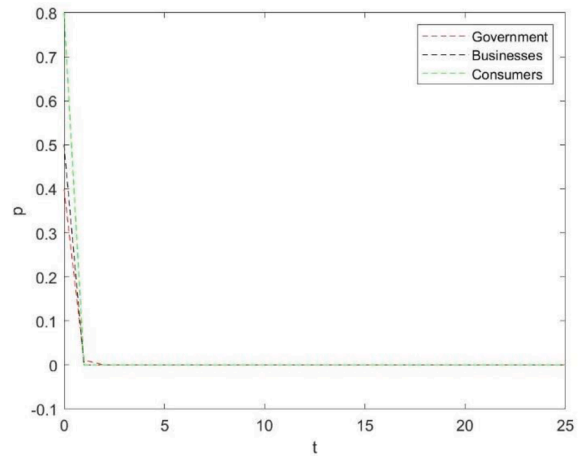

(b). Dynamic process of two-dimensional tripartite evolutionary game under the first class

Fig. 9(a). Dynamic process of three-dimensional tripartite evolutionary game under the first class.
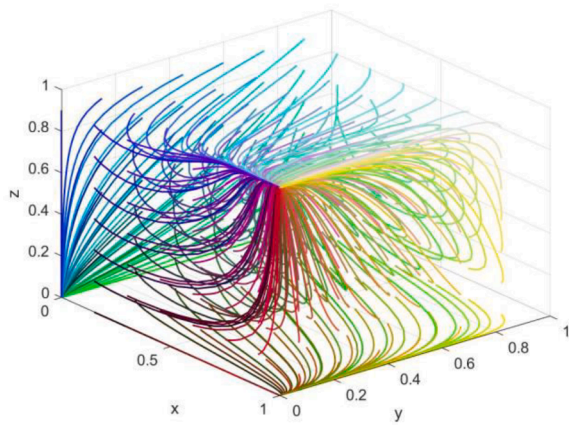
(a). Dynamic process of three-dimensional tripartite evolutionary game under the second class
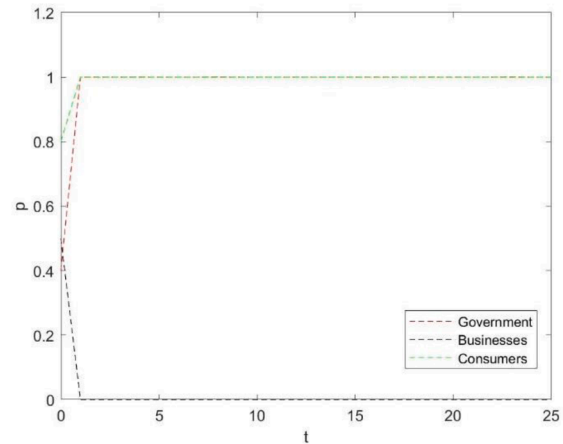

(b). Dynamic process of two-dimensional tripartite evolutionary game under the second class

Fig. 9(b). Dynamic process of two-dimensional tripartite evolutionary game under the second class.

(a). Dynamic process of three-dimensional tripartite evolutionary game under the third class

(b). Dynamic process of two-dimensional tripartite evolutionary game under the third class
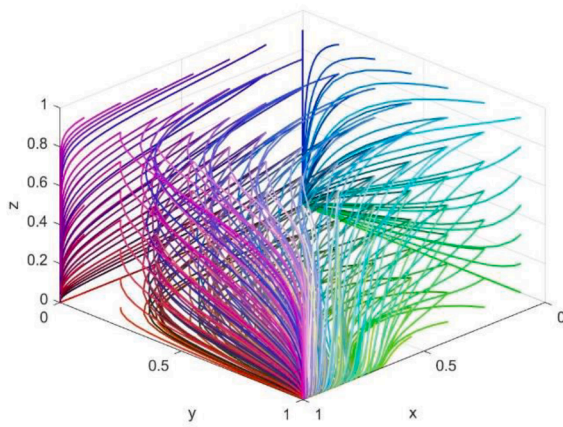
Fig. 10(a). Dynamic process of three-dimensional tripartite evolutionary game under the third class.

important than the subsidy mechanism. Regardless of the subsidy mechanism given, at high penalty levels, the government, businesses and consumers have incentives to participate in the fight against COVID-19. On the contrary, under the low penalty mechanism, all three parties lack incentives to fight the COVID-19. Our findings make clear the importance of punishment mechanisms after governments enact restrictive policies. We believe that the reason why the penalty mechanism works better than the subsidy mechanism may be that the subsidy mechanism allows the participants to "free ride." For the government, the excessive subsidy level will lead to the increase of the cost of fighting the COVID-19. We take Japan as an example.

The Japanese government's initial response to the COVID-19 outbreak was to adopt a containment policy. On January 24, 2020, it announced that it would coordinate with National Institute of Infectious Diseases (NIID) to propose appropriate policies to prevent and control the disease. On January 27, 2020, in accordance with the Quarantine Law, those suspected of being infected were quarantined with testing and treatment mandated. The Japanese government has prioritized the establishment of COVID-19 testing and counselling systems based on the

NIID. In addition, it has set up a dedicated consultation center for COVID-19 and has promised to provide a large quantity of testing re-agents. The Japanese government has decided that prevention of mass clusters of disease in Japan will be a priority in its disease response, such as suspending mass gatherings, community events, school operations and restricting access to medical facilities by patients with mild cold symptoms to prevent them from taking up hospital resources. The government also urged companies to allow employees to work from home or commute during off-peak hours. The government has also formally asked local governments and companies to cancel major events.

On February 12, 2020, the Japanese government announced that it would provide ¥500 billion in emergency loans and loan guarantees for small and medium-sized businesses affected by COVID-19. It also announced that the cabinet would allocate 15.3 billion yen from the emergency fund to facilitate the donation of isolated virus samples to relevant research institutions around the world. On March 10, 2020, a second emergency plan was announced, focused on increasing hospital beds for infected patients, increasing loan support for businesses, and

(a). Dynamic process of three-dimensional tripartite evolutionary game under the fourth class
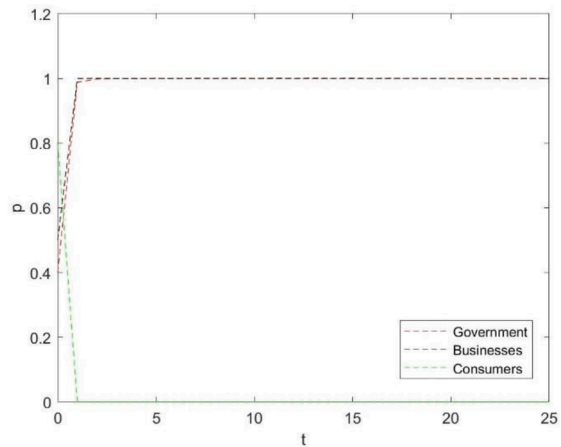
(b). Dynamic process of two-dimensional tripartite evolutionary game under the fourth class

Fig. 10(b). Dynamic process of two-dimensional tripartite evolutionary game under the fourth class.

strengthening employment support. As a special measure implemented from April 1 to December 31, the Ministry of Labor and Welfare has offered leave subsidies of up to 100 percent for small and medium-sized businesses and up to 80 percent for large businesses. The allowance for each employee on leave was capped at ¥15,000 per day. This supplemental income policy has caused problems. When the ¥300,000 per household policy was changed to a ¥100,000 per household population policy, it encountered many obstacles. The Japanese government has organized an emergency plan to use a reserve fund of 270 billion yen ($2.5 billion) for the fiscal year ending March 2021 to contain the virus and minimize its impact on the economy.

Japan has been praised for keeping the number of infections low without having to enforce strict rules. As the number of infected people soared, the Japanese government began to rethink the so-called "Japanese model" of voluntary compliance in early November 2020. In February 2021 legislation was introduced to fine those who violate social distancing rules. Kaori et al. [3] studied the changes in the behavior of Japanese citizens during COVID-19 due to the implementation of restrictive measures by the Japanese government. They found that about most people reported taking government-recommended distance measures, with women and older people more likely to cooperate. However, the results of the study also showed that about 20 percent of participants were reluctant to take proper precautions.

The results of our study are generalized. It can be applied in any country or region. For example, in the above analysis results, we find that the basic utility of consumers is also an important factor affecting the government's punishment subsidy mechanism. Therefore, different countries or regions attach different importance to health due to cultural differences. Consumers in some countries or regions regard life and health as the most important. Consumers in these countries and regions would have enough incentive to choose active prevention strategies (because they have basic utility). Consumers in other countries and regions regard freedom and other unhealthy things like consumption as the most important. Therefore, they have no fundamental utility. Governments need to rely on sufficiently stringent penalties to persuade those consumers to opt for active prevention strategies.

Although further empirical work in this area is required, our study sheds light on the strategic interaction of government, businesses and

citizens and helps us understand the role of subsidies and penalties in supporting or undermining unity in fighting this and possible future pandemics. We believe that too low a penalty will not enable governments, businesses, and consumers to fight the pandemic together. High costs caused by excessive subsidies could reduce the government's incentive to fight the pandemic. Low penalty levels do not create enough incentives for businesses and consumers to respond positively to the pandemic. In the context of COVID-19, the punishment mechanism is superior to the subsidy mechanism. The government's implementation of a high penalty mechanism will quickly and effectively give businesses and consumers the option of active prevention.

It is also apparent that internal motivations are influential. The cultural background of a country (e.g. Asian Confucianism and Buddhism versus European liberalism) as well as trust in government will have an important impact on the decisions made by participants and ultimately the equilibrium reached. It is also worth noting that the penalty and subsidy mechanisms implemented are likely to impact citizens' level of trust in government. This provides a potential avenue for future research using game theory.

CRediT authorship contribution statement

Yuxun Zhou: Conceptualization, Methodology, Software, Formal analysis, Writing – original draft. **Mohammad Mafizur Rahman:** Supervision, Writing – review & editing, Project administration. **Rasheda Khanam:** Supervision, Writing – review & editing, Project administration. **Brad R. Taylor:** Supervision, Writing – review & editing, Project administration, Resources.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The data that has been used is confidential.

Appendix A. Proof of Propositions

A.1. Proof of *Proposition 1*

If point $(1, 0, 0)$ is an evolutionary stable point, $a_{17} - a_{27} + a_{12} - a_{18} + a_{112} - a_{19} < 0$ and $(a_{17} - a_{27})(a_{12} - a_{18})(a_{112} - a_{19}) > 0$. The necessary condition is $a_{17} < a_{27}$, $a_{12} < a_{18}$ and $a_{112} < a_{19}$. According to assumption 1, 2 and 3, we have the following inequations: $c_p^C + c_p^M - c_0 - R_M - R_C^r < 0$, $c_p^M < S^M$ and $u_h + S_G^C - u_o - W_0 - W + c_m^C + c_p^C < 0$ We can deduce: $c_p^C + c_p^M < c_0 + R_M + R_C^r$ and $c_p^C + S_G^C < u_o + W_0 + W - c_m^C - u_h$. Thus, $(1, 0, 0)$ is an

ESS point, if
$$\begin{cases} c_p^C + c_p^M \in [0, \ c_0 + R_M + R_C^r) \\ c_p^C + S_G^C \in [0, \ u_o + W_0 + W - c_m^C - u_h) . \\ c_p^M \in [0, \ S^M) \end{cases}$$

A.2. Proof of *Proposition 2:*

If point $(0, 1, 0)$ is an evolutionary stable point, $a_{11} - a_{21} + a_{22} - a_{28} + a_{26} - a_{23} < 0$ and $(a_{11} - a_{21})(a_{22} - a_{28})(a_{26} - a_{23}) > 0$. The necessary condition is $a_{11} < a_{21}$, $a_{22} < a_{28}$ and $a_{26} < a_{23}$. According to assumption 1, 2 and 3, we have the following inequations: $u_b + 2R_M + c_p^C - S_G^M - c_0 - c_c^G$

$- R_C^r < 0$, $S^M > 0$ and $u_h - u_o - W + c_m^C < 0$. We can deduce the necessary condition: $\begin{cases} S_G^M - c_p^C > u_b + 2R_M - c_0 - c_c^G - R_C^r \\ u_h - u_o - W + c_m^C < 0 \end{cases}$.

A.3. Proof of *Proposition 3*

If point $(1, 1, 1)$ is an evolutionary stable point, The necessary condition is $a_{24} < a_{14}$, $a_{111} < a_{15}$ and $a_{13} < a_{16}$. According to assumption 1, 2 and 3, we have $S_G^M + S_G^C < u_b + 2R_M + 2R_C^a - c_0$, $c_p^M > S^M$ and $S_G^C + c_p^C > u_o + W - c_m^C - u_h$. $(1, 1, 1)$ is an evolutionary stable strategy, if it satisfied the

condition:
$$\begin{cases} S_G^M + S_G^C \in [0, \ u_b + 2R_M + 2R_C^a - c_0) \\ c_p^M \in (S^M, \ +\infty) \\ S_G^C + c_p^C \in (u_o + W - c_m^C - u_h, \ +\infty) \end{cases}$$

A.4. Proof of *Proposition 4*

If point $(0, 0, 0)$ is an evolutionary stable point, The necessary condition is $a_{17} < a_{27}$, $a_{22} < a_{28}$ and $a_{212} < a_{29}$. According to assumption 1, 2 and 3, we have $c_p^C + c_p^M - c_0 - R_M - R_C^r < 0$, $S^M > 0$ and $u_h - u_o - W_0 - W + c_m^C < 0$. $(0, 0, 0)$ is an evolutionary stable strategy, if it satisfied the condition: $c_p^C + c_p^M \in [0, \ c_0 + R_M + R_C^r)$

A.5. Proof of *Proposition 5*

If point $(0, 0, 1)$ is an evolutionary stable point, $a_{110} - a_{210} + a_{25} - a_{211} + a_{212} - a_{29} < 0$ and $(a_{110} - a_{210})(a_{25} - a_{211})(a_{212} - a_{29}) > 0$. The necessary condition is $a_{110} < a_{210}$, $a_{25} < a_{211}$ and $a_{212} < a_{29}$. It contradicts with the assumption: $a_{29} > a_{212}$ that we mention in the assumption 1. Thus, $(0, 0, 1)$ is not an evolutionary stable point.

If point $(0, 1, 1)$ is an evolutionary stable point, $a_{14} - a_{24} + a_{25} - a_{211} + a_{26} - a_{23} < 0$ and $(a_{14} - a_{24})(a_{25} - a_{211})(a_{26} - a_{23}) > 0$. The necessary condition is $a_{14} < a_{24}$, $a_{25} < a_{211}$ and $a_{26} < a_{23}$. It contradicts with the assumption: $a_{14} > a_{24}$ that we mention in the assumption 1. Thus, $(0, 1, 1)$ is not an evolutionary stable point.

If point $(1, 0, 1)$ is an evolutionary stable point, $a_{210} - a_{110} + a_{15} - a_{111} + a_{112} - a_{19} < 0$ and $(a_{110} - a_{210})(a_{15} - a_{111})(a_{112} - a_{19}) > 0$. The necessary condition is $a_{210} < a_{110}$, $a_{15} < a_{111}$ and $a_{112} < a_{19}$. It contradicts with the assumption: $a_{15} > a_{111}$ that we mention in the assumption 1. Thus, $(1, 0, 1)$ is not an evolutionary stable point

If point $(1, 1, 0)$ is an evolutionary stable point, the necessary condition is $a_{11} < a_{21}$, $a_{12} < a_{18}$ and $a_{16} < a_{13}$. It contradicts with the assumption: $a_{16} > a_{13}$ that we mention in the assumption 1. Thus, $(1, 1, 0)$ is not an evolutionary stable point.

If point $(0, 1, 1)$ is an evolutionary stable point, $a_{14} - a_{24} + a_{25} - a_{211} + a_{26} - a_{23} < 0$ and $(a_{14} - a_{24})(a_{25} - a_{211})(a_{26} - a_{23}) > 0$. The necessary condition is $a_{14} < a_{24}$, $a_{25} < a_{211}$ and $a_{26} < a_{23}$. It contradicts with the assumption: $a_{14} > a_{24}$ that we mention in the assumption 1. Thus, $(0, 1, 1)$ is not an evolutionary stable point.

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